Infrared Sources and Detectors for Deep-Space Science

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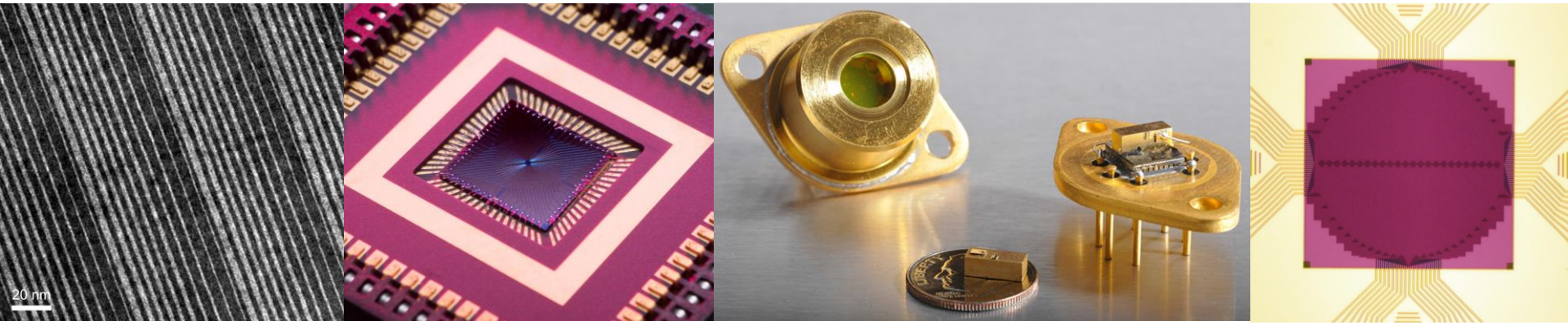

Jet Propulsion Laboratory
California Institute of Technology

Acknowledgements

QC Lasers:

- Coworkers:

Clifford Frez, Mathieu Fradet, Mahmood Bagheri, Siamak Forouhar, and Chris Webster, *JPL*

Christian Pflügl, Romain Blanchard, and Laurent Diehl, *Pendar Technologies*

- Project support:

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NASA New Frontiers Homesteader Program

SNSPDs:

- Coworkers:

Matthew Shaw, Andrew Beyer, Francesco Marsili, Jason Allmaras, and Bill Farr, *JPL*

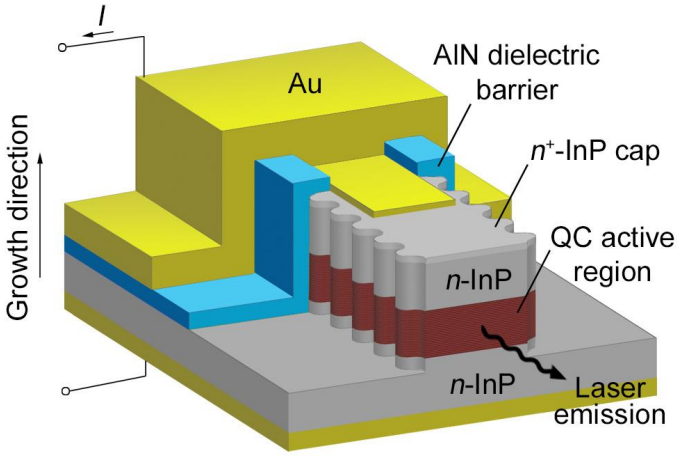
- Project support:

NASA Game Changing Development Program

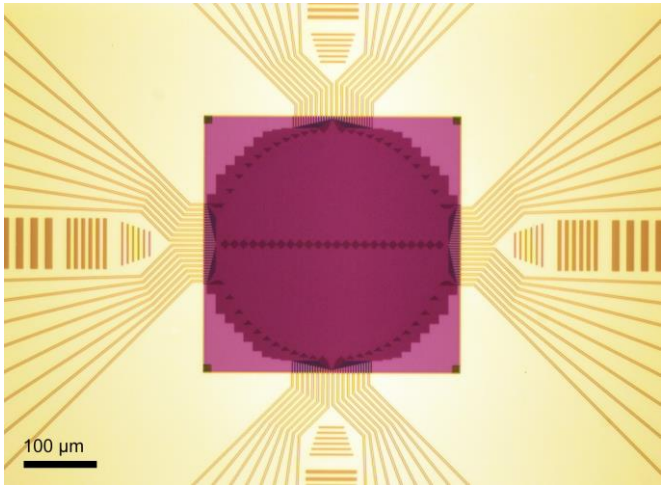
JPL Research And Technology Development Program

Overview

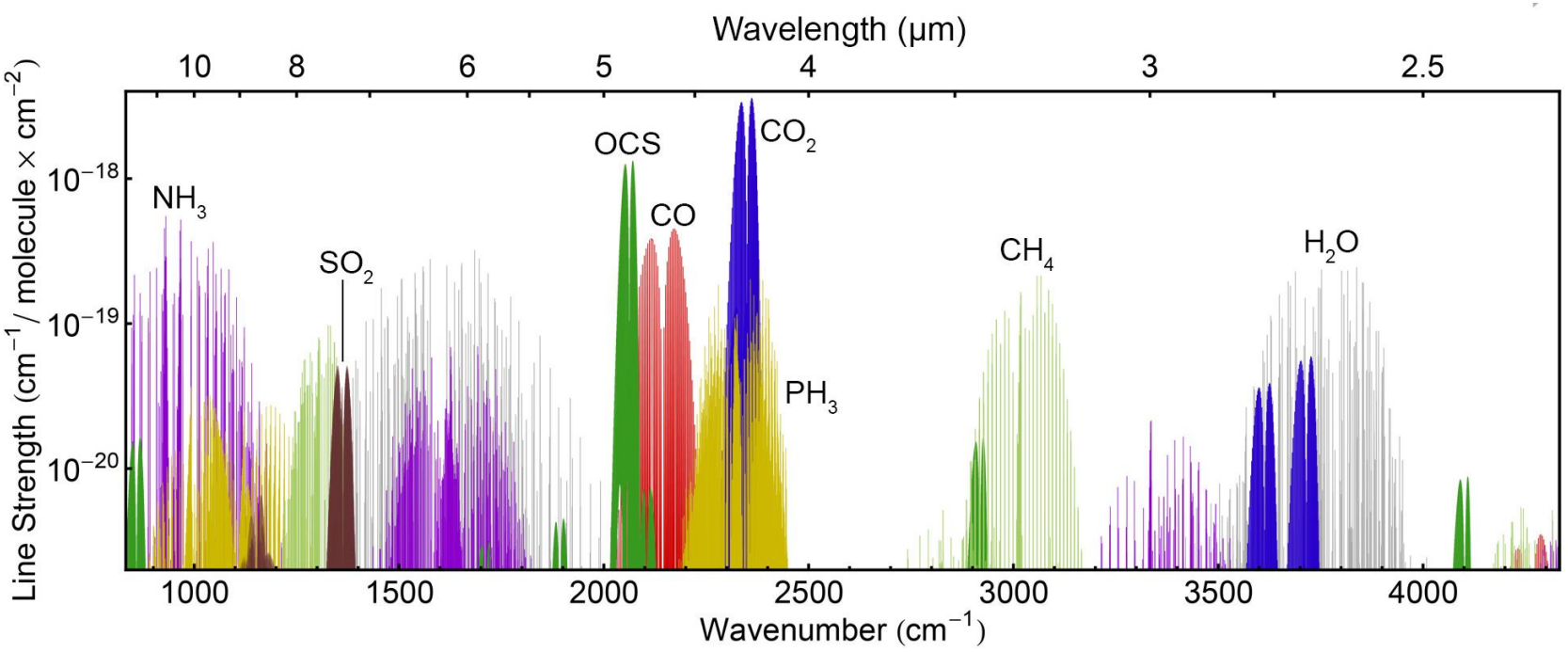
Low-power consumption quantum cascade (QC) lasers for *in situ* gas absorption spectroscopy



Superconducting nanowire single-photon detector (SNSPD) arrays for deep space optical communication

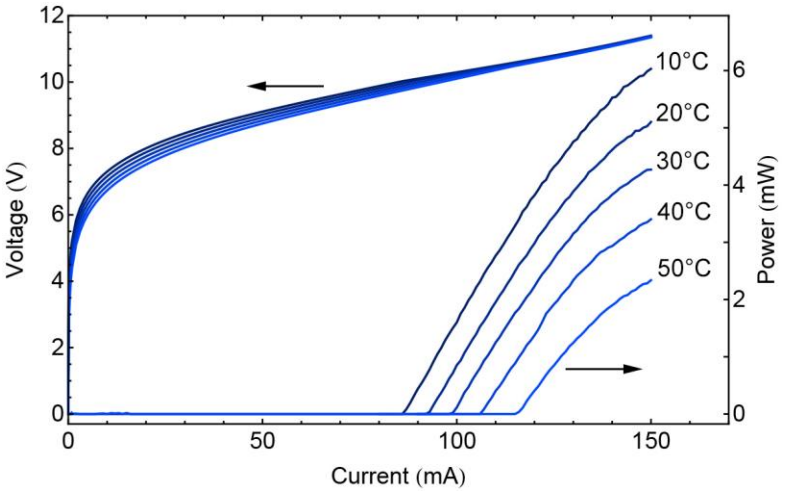


Molecular absorption in the mid-infrared regime



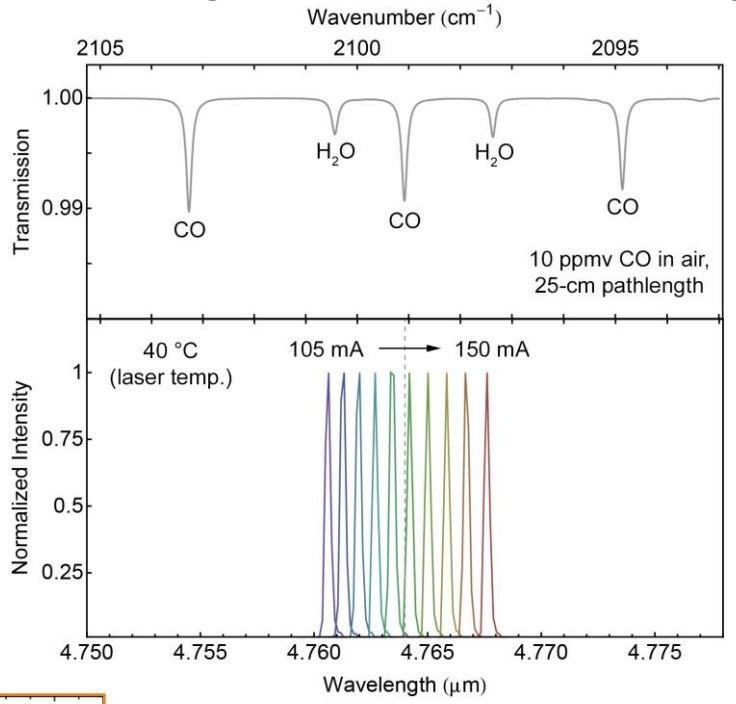
Laser wavelength modulation spectroscopy

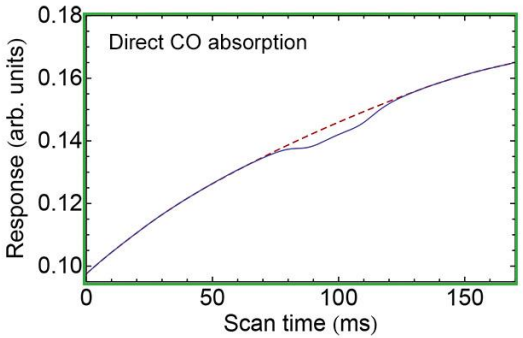
Laser light-current-voltage characteristics

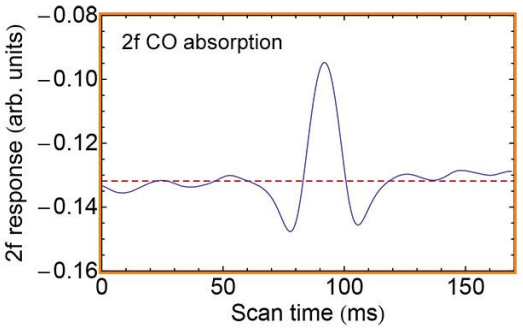


By sweeping current sourced to a single-mode laser, relative absorption is measured over a known pathlength

Current tuning of laser emission wavelength



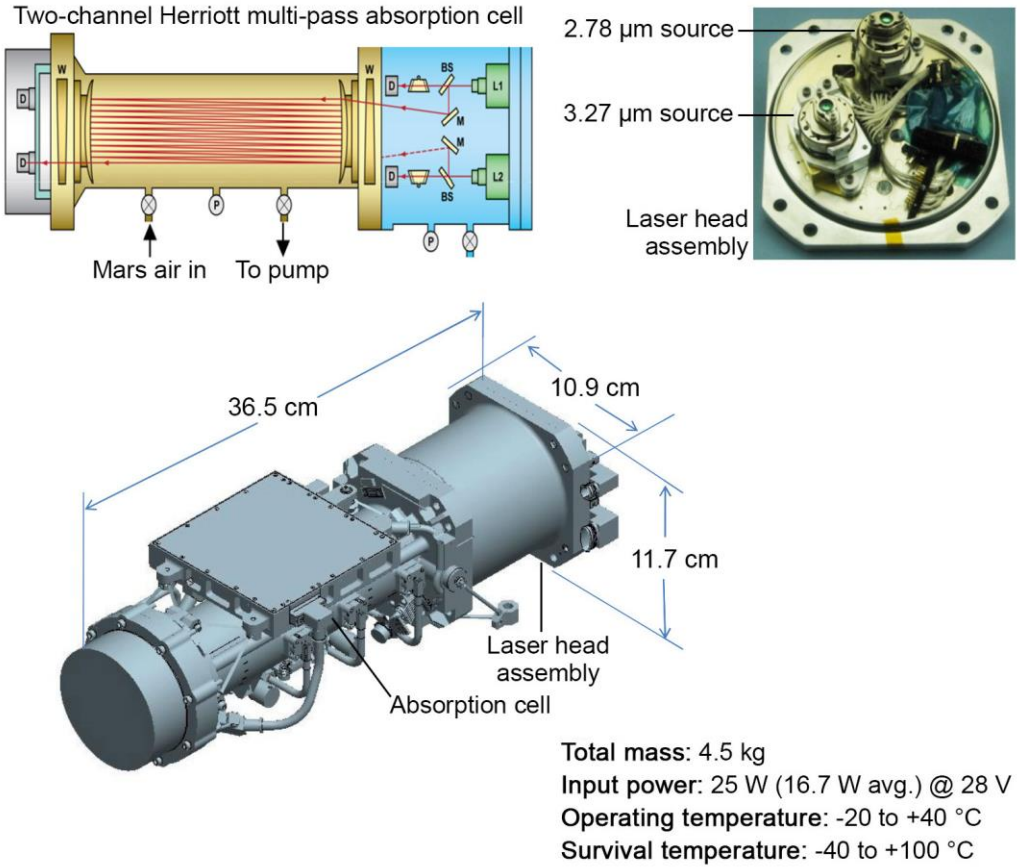




With additional small-amplitude modulation of the current, the demodulated spectral response can be measured with reduced noise

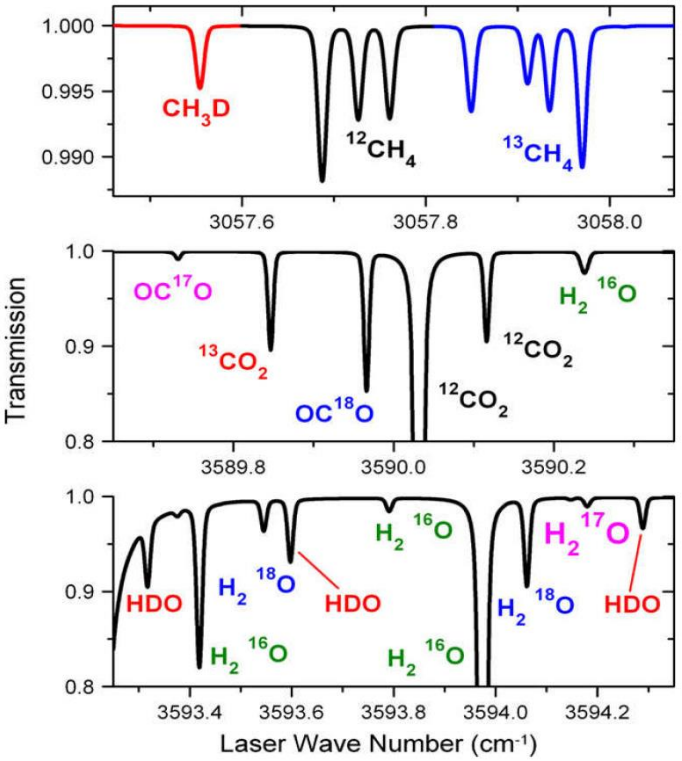
Tunable Laser Spectrometer (TLS) on the Mars Curiosity rover

TLS instrument layout for CH_4 and CO_2/H_2O detection



Total mass: 4.5 kg
Input power: 25 W (16.7 W avg.) @ 28 V
Operating temperature: -20 to +40 °C
Survival temperature: -40 to +100 °C

Target absorption lines



Webster, *et al.*, *Science* **341**, 260 (2013)
Webster, *et al.*, *Science* **347**, 415 (2015)

Tunable Laser Spectrometer (TLS) on the Mars Curiosity rover

C, O, and H isotope ratios in Martian atmosphere

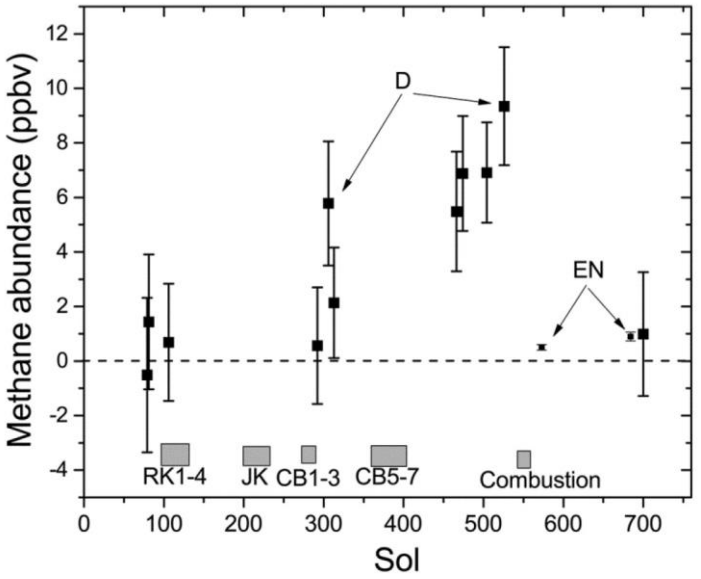
Table 1. Carbon dioxide isotope ratios ‰ ± 2 SEM (standard error of the mean). *, not measured.

Measurement	$\delta^{13}C$	$\delta^{18}O$	$\delta^{17}O$	$\delta^{13}C^{18}O$
SAM-TLS	46 ± 4	48 ± 5	24 ± 5	109 ± 31
SAM-QMS (*3*)	45 ± 12	*	*	*
Phoenix lander (*12*)	−2.5 ± 4.3	31.0 ± 5.7	*	*
Viking Neutral Mass Spectrometer (*11*)	23 ± 43	7 ± 44	*	*
SNC meteorites (*8*, *12*, *32*)	36 ± 10	3.9–5.4 ± 0.1	~0.53* $\delta^{18}O \sim \delta^{13}C + \delta^{18}O$	
ALH84001 meteoritic carbonate range (*30*, *31*)	27 to 64	−9 to 26	~0.53* $\delta^{18}O \sim \delta^{13}C + \delta^{18}O$	
ALH84001 meteoritic carbonate mean value (*31*)	46 ± 8	4.6 ± 1.2	*	*
Earth telescopes (*9*)	−22 ± 21	18 ± 18	*	*

Table 2. Water isotope ratios ‰ ± 2 SEM. *, not measured.

Measurement	δD	$\delta^{18}O$
SAM-TLS atmosphere	4950 ± 1,080	*
SAM-TLS evolved water: Rocknest fines 230° to 430°C (*23*)	5880 ± 60	84 ± 10
Meteoritic crustal reservoirs (*26*)	~5000	*
Earth telescopes (*24*)	1700–8900	*
ALH 84001 (*17*)	3000	*
Shergotty USNM 321-1 (*17*)	4600	*

Methane abundance on Mars



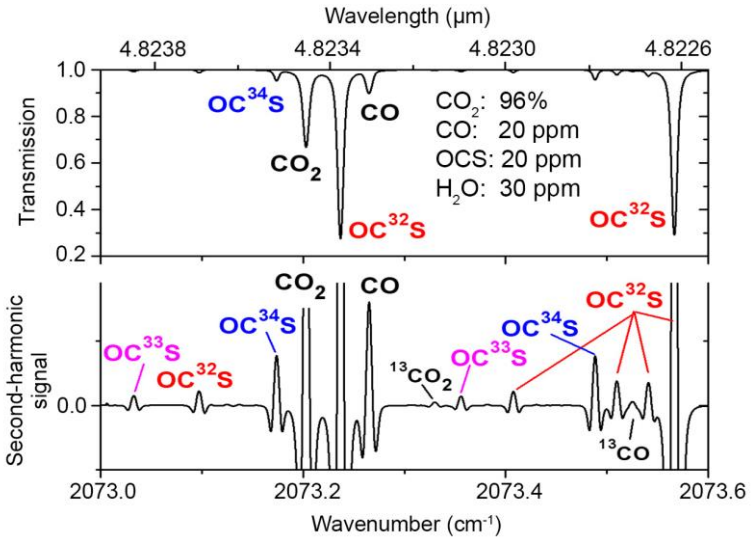
Webster, *et al*., *Science* **341**, 260 (2013)
Webster, *et al*., *Science* **347**, 415 (2015)

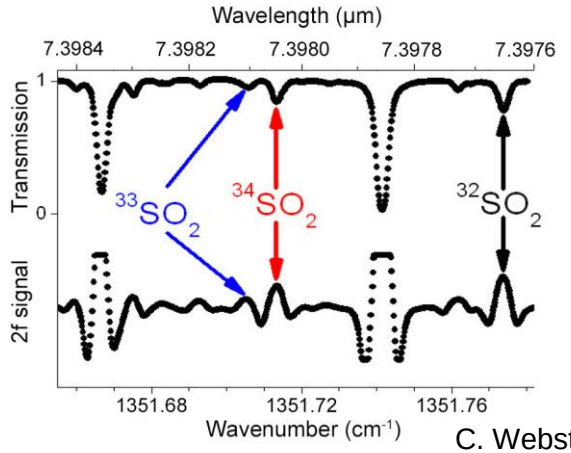
Future planetary science instruments: Venus In Situ Explorer

Venus In Situ Explorer
atmospheric probe concept

NASA

Target molecules: OCS and SO_2

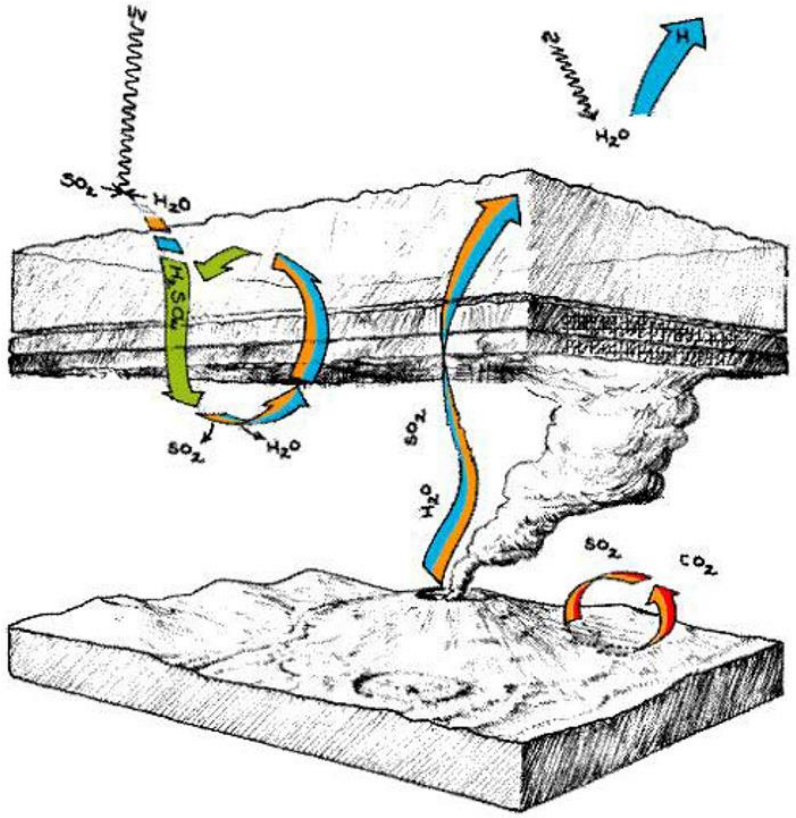




C. Webster, JPL

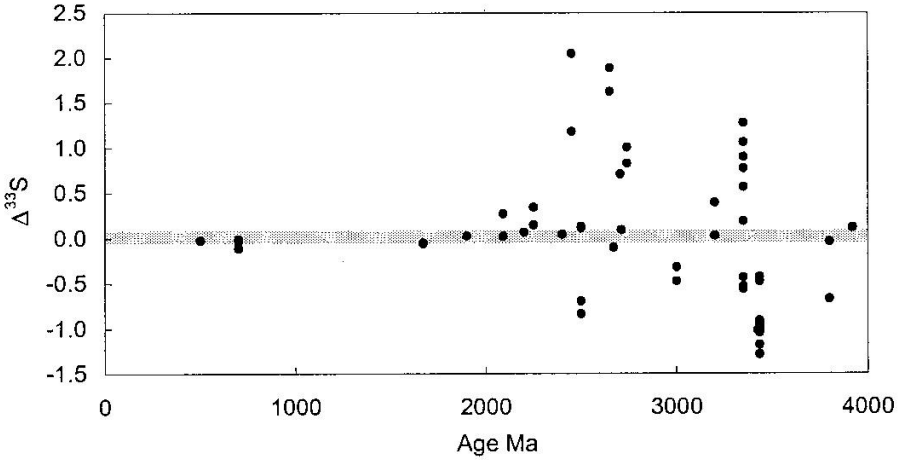
Future planetary science instruments: Venus In Situ Explorer

Photolysis and the sulfur cycle on Venus



D. Grinspoon and C. Emmart, NASA

Geological sulfur isotope record on Earth

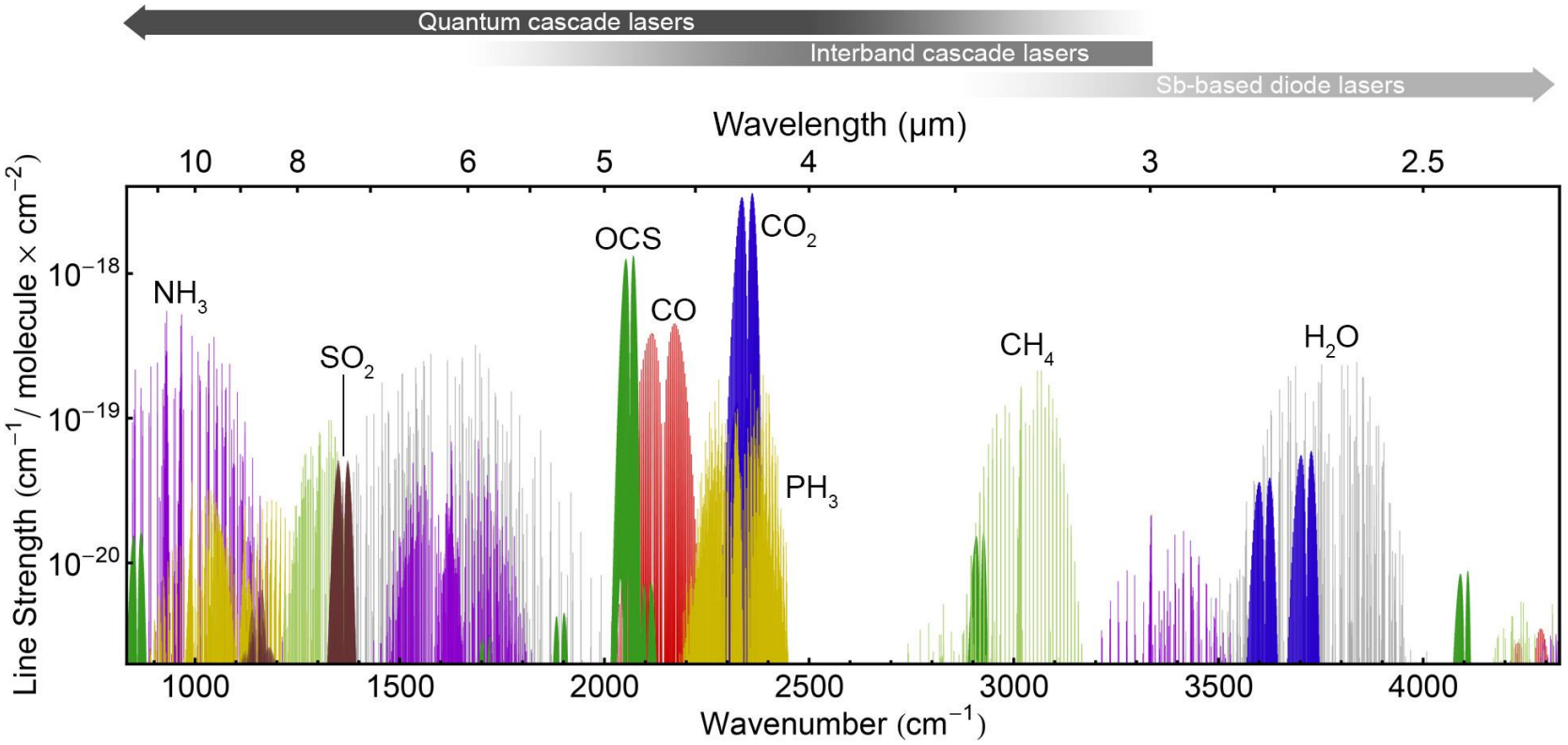


Farquhar, *et al.*, Science **289**, 756 (2000)

S isotope measurements are a primary objective for proposed missions to Venus

Isotope ratios are key to understanding climate cycles on Venus and can verify theories of the evolution of Earth's atmosphere

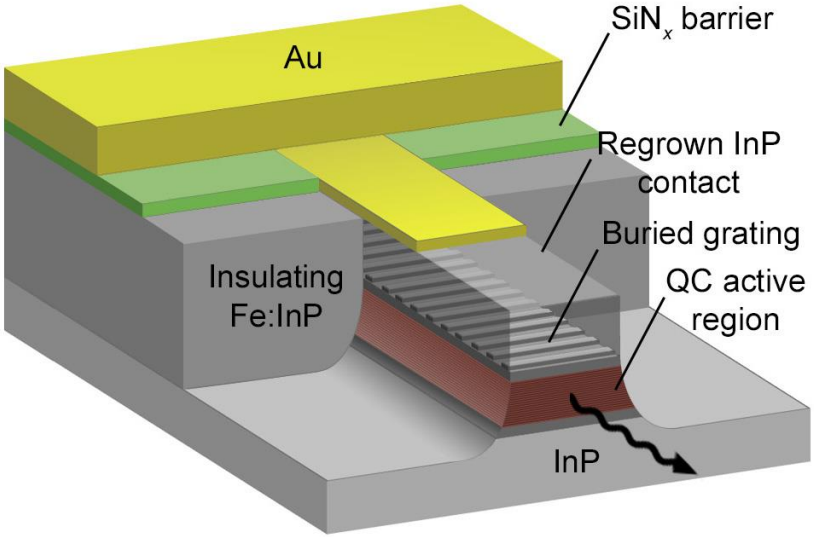
Semiconductor laser technologies for TLS instruments

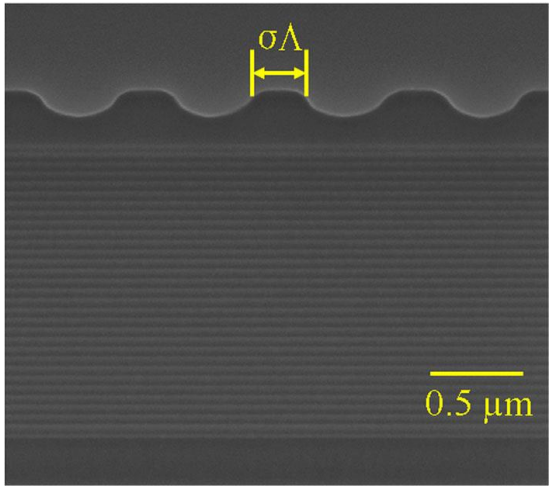


Future laser spectrometers will target longer-wavelength lines, which will require QC lasers

Power consumption is a limiting factor in component selection

Buried-heterostructure DFB QC lasers

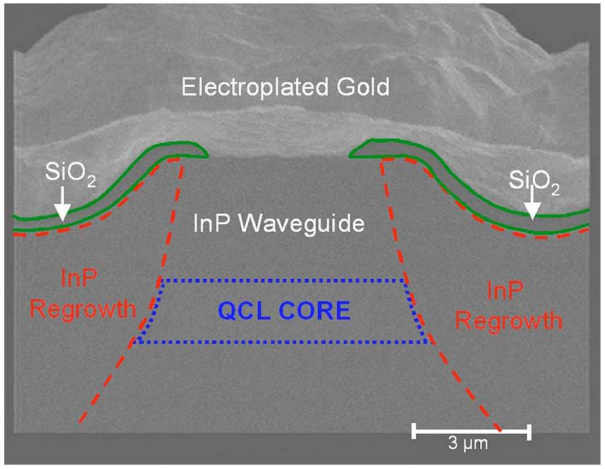




Zhang, *et al*., *Appl. Phys. Lett.* **100**, 112105 (2012)

Provides low optical loss, excellent heat dissipation, and reliability, but requires two epitaxial regrowth processes

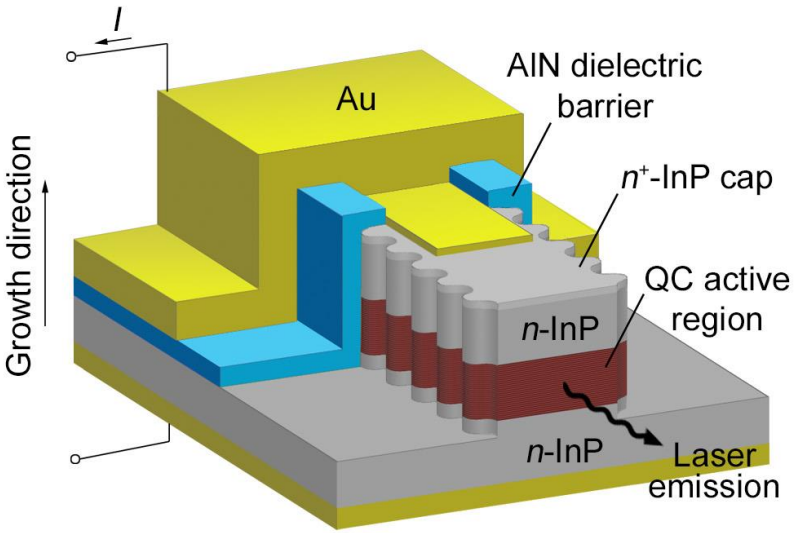
Mid-infrared emission with sub-watt power consumption recently demonstrated by ETH Zürich and Alpes Lasers



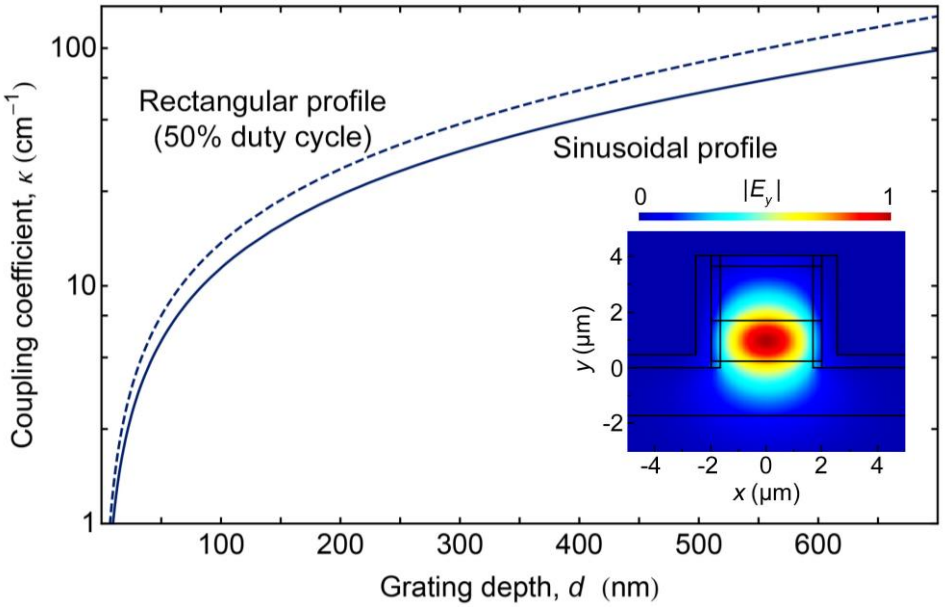
Evans, *et al*., *Appl. Phys. Lett.* **91**, 071101 (2007)

Hinkov, *et al*., *Electron. Lett.* **646**, 071101 (2012)
Bismuto, *et al.*, *Opt. Express* **23**, 5477 (2015)

Regrowth-free DFB QC laser design



Calculated grating coupling coefficient:
4.8 μm wavelength, 775 nm pitch

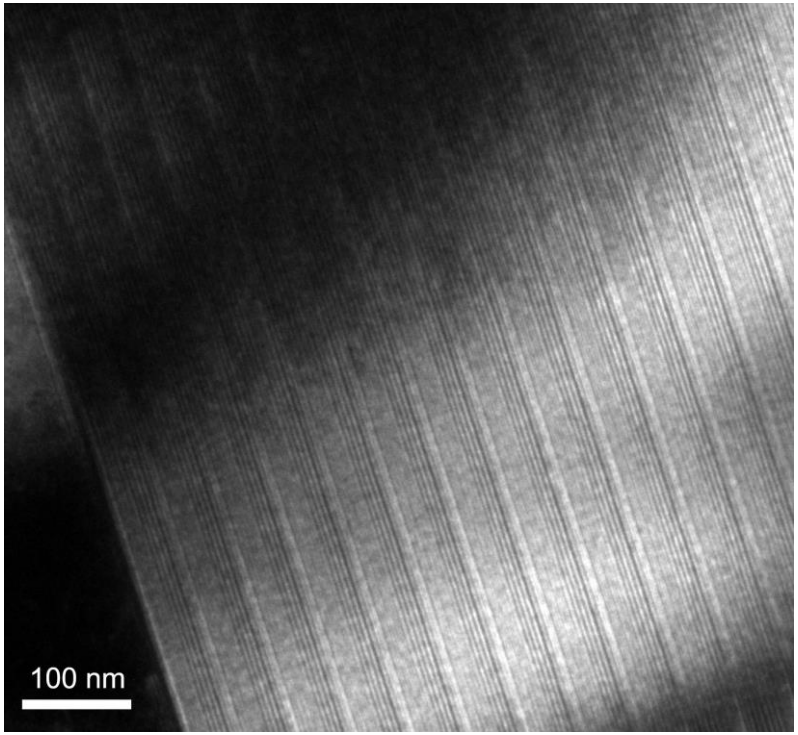


Sidewall gratings with low-index dielectric cladding provide high optical confinement

Narrow, vertically etched ridges enable low-current operation

Fabrication of DFB QC lasers

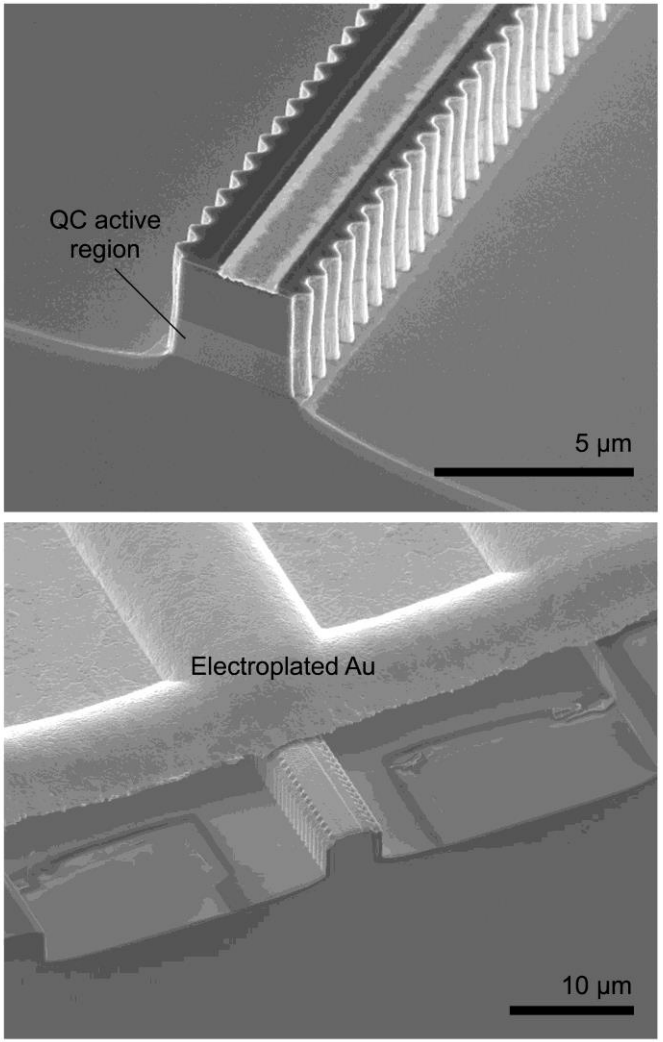
MBE-grown QC active region on InP



Transmission electron microscopy by M. Sullivan (Caltech)

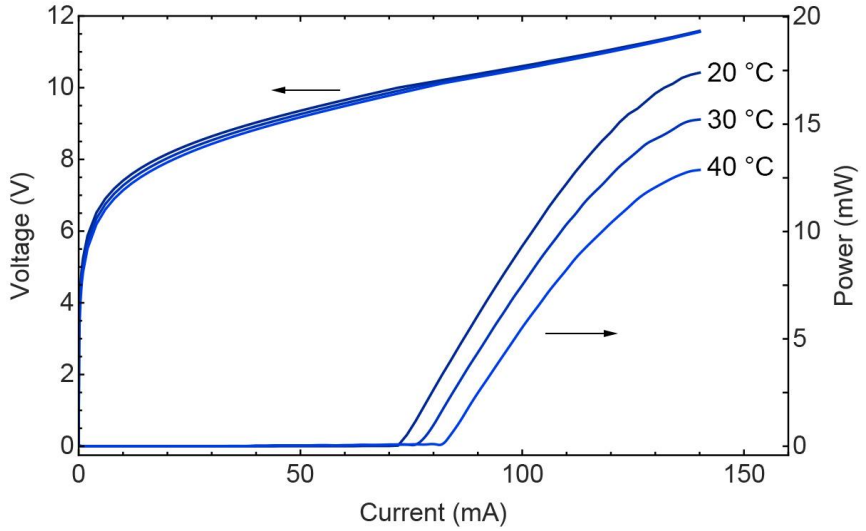
Two-phonon-resonance design used <5 μm,
non-resonant extraction designs employed >5 μm

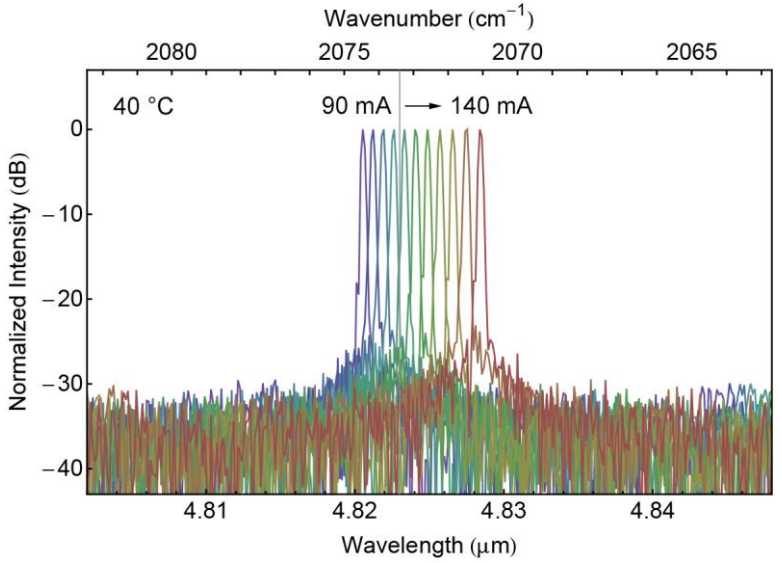
Processed DFB QC lasers

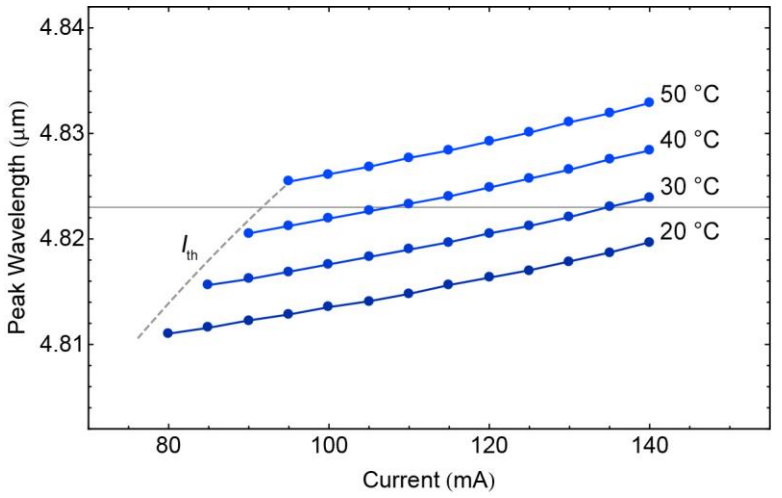


DFB QC laser performance: 4.8 µm wavelength for OCS detection

CW performance: 1 mm cavity, HR-coated back facet







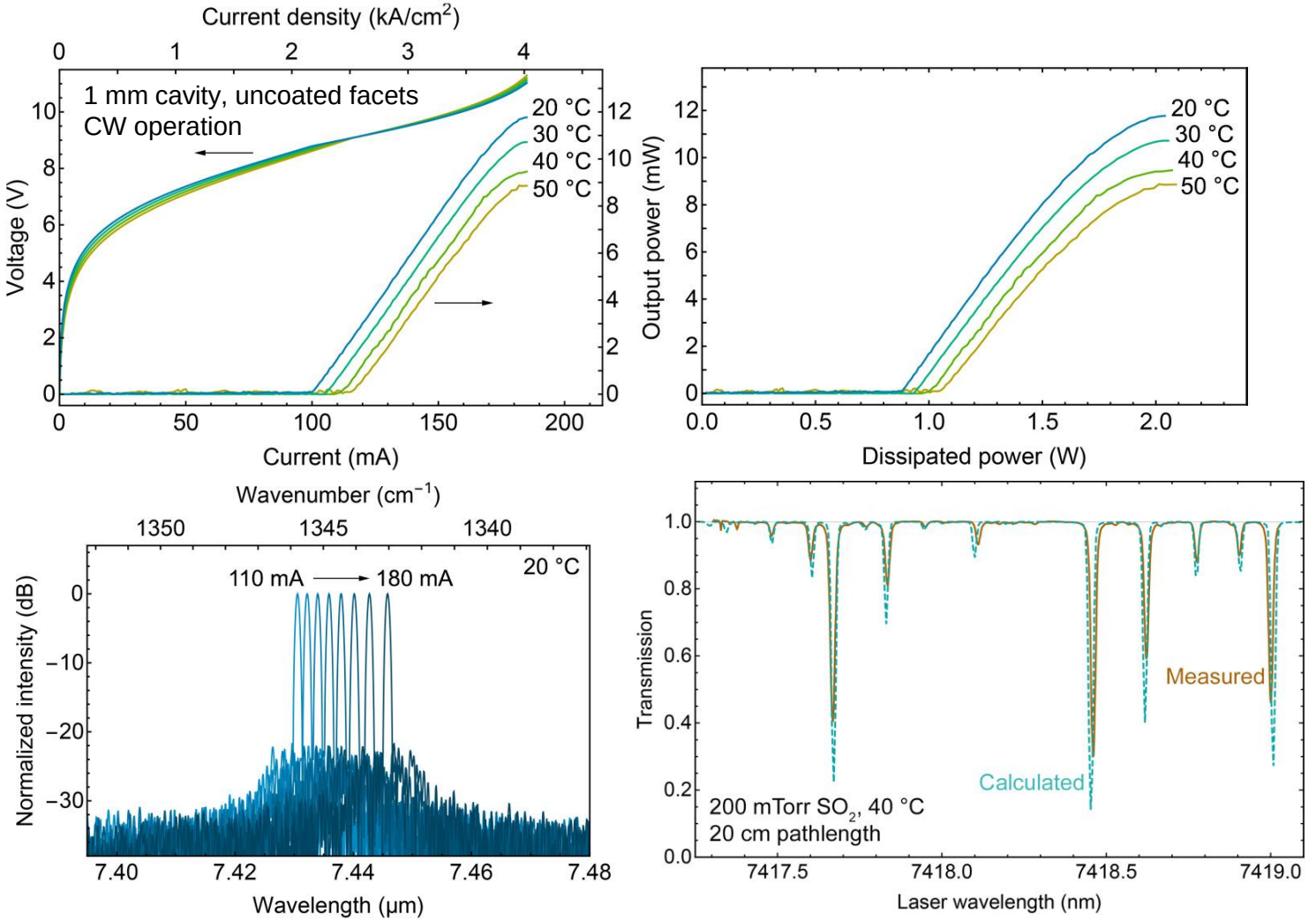
Stable, single-mode emission with 750 mW CW threshold power consumption at 20 ° C

Mode-hop-free tuning across target wavelength above room temperature

Devices have been run for as long at 2000 hours without degradation

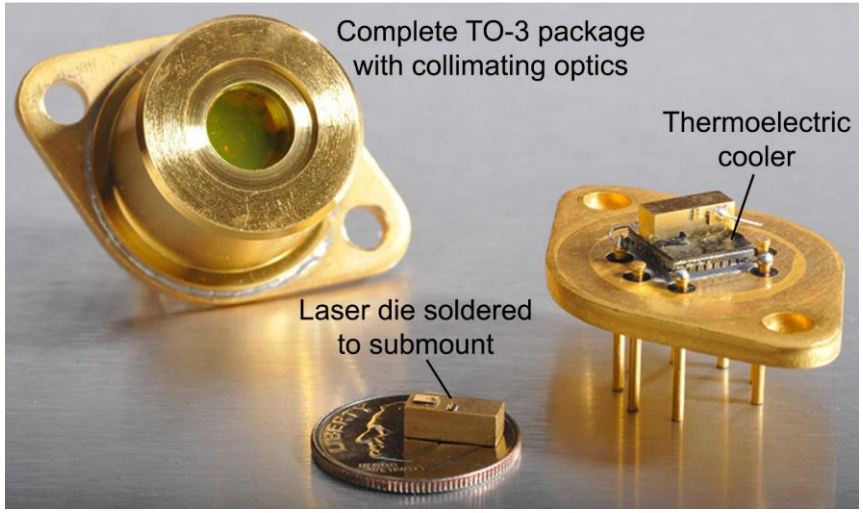
Briggs, *et al.*, *Appl. Phys. Lett.* **105**, 141117 (2014)

DFB QC laser performance: 7.4 µm wavelength for SO_2 detection



Briggs, *et al.*, *Opt. Express* **24**, 14589 (2016)

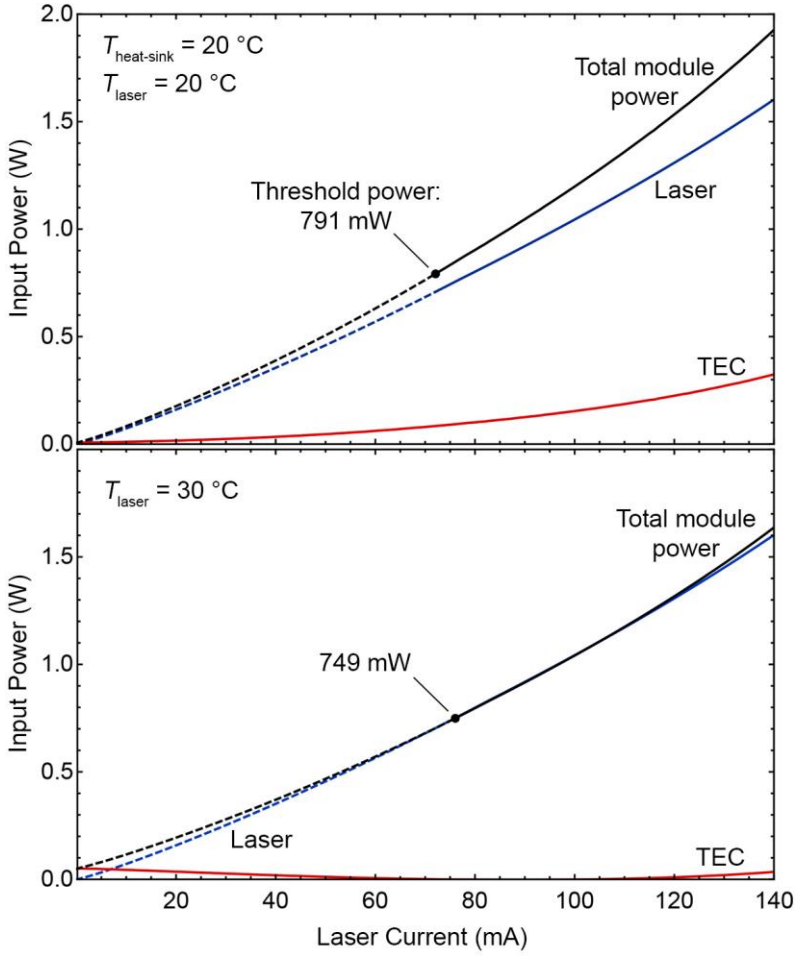
QC laser packaging



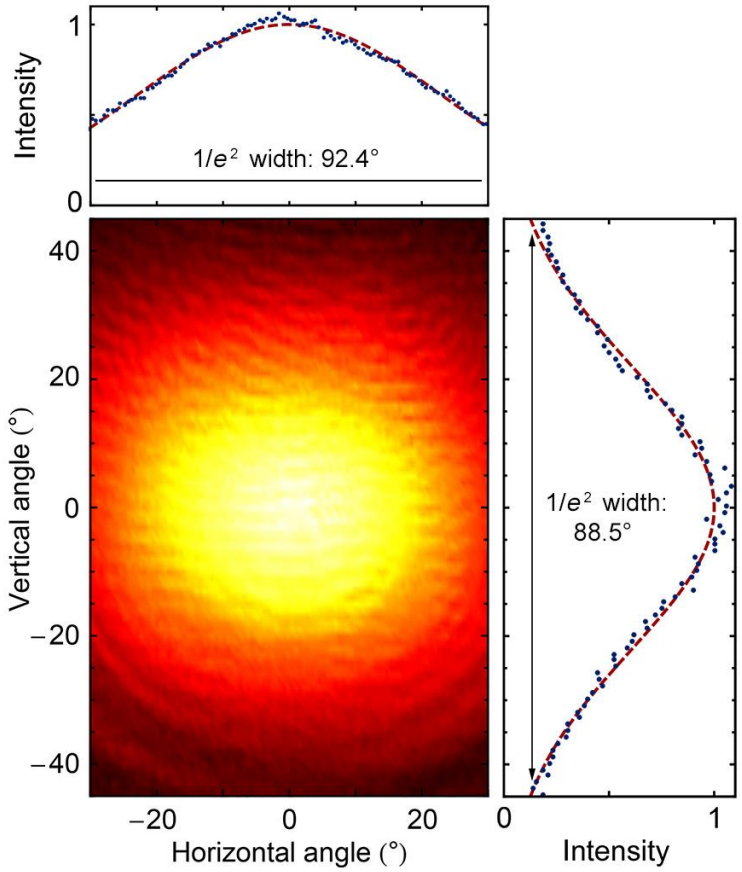
Low dissipation and high operating temperatures enable use of small form factor packages

Demonstrated modules with power consumption <1 W at threshold and <2 W at maximum output

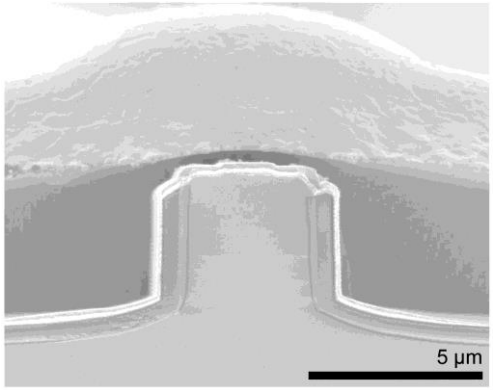
Packaged 4.8 µm QC laser CW power consumption

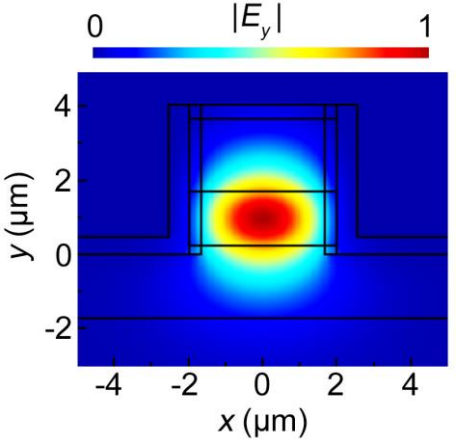


Symmetric QC laser far-field profile



Measured far-field profile at 4.8 µm





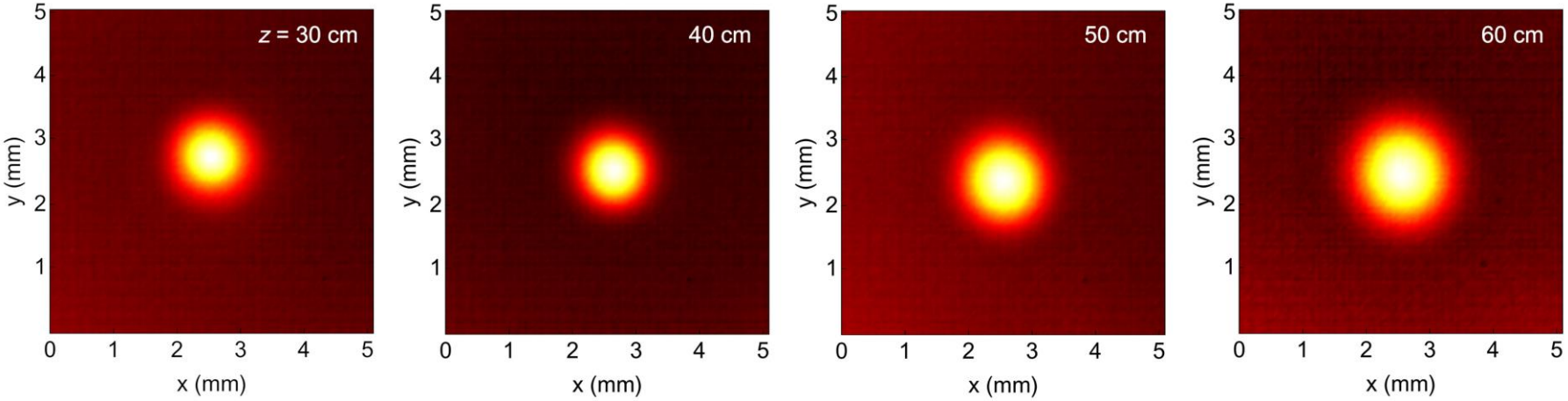
Briggs, *et al.*, *Appl. Phys. Lett.* **105**, 141117 (2014)

Low-index lateral cladding compensates for the asymmetric active region, resulting in a radially symmetric far-field profile

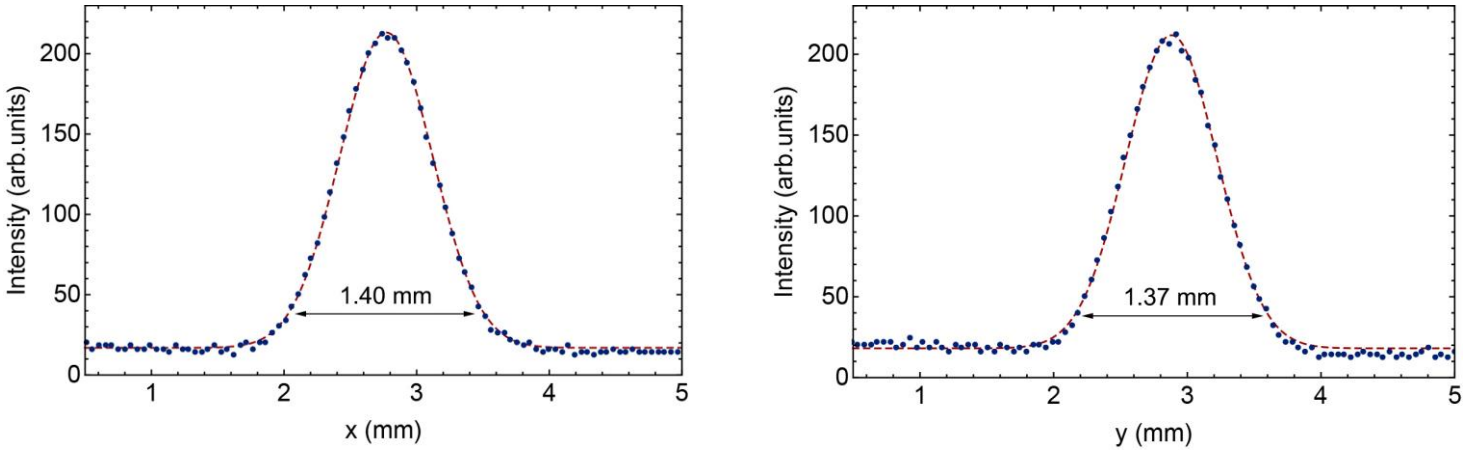
Enables efficient coupling to external optics

Beam profiles for 7.4 µm QC laser: Single aspheric collimating lens

Infrared camera images at varying distance, *z*, from the lens

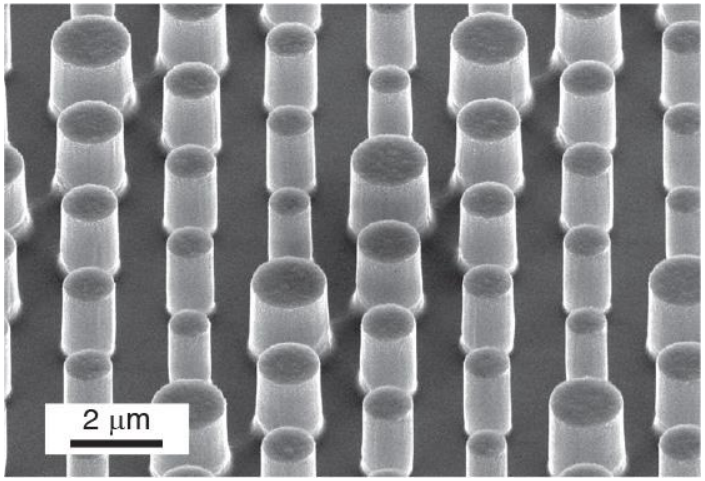


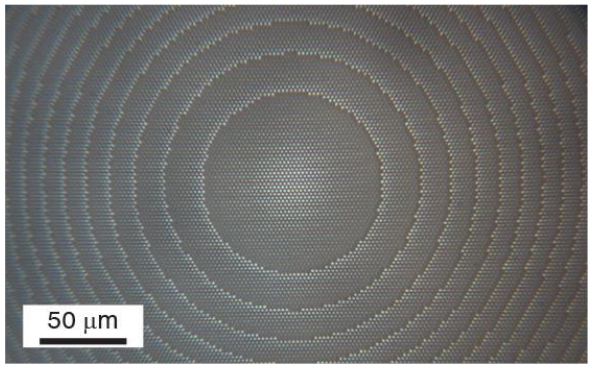
Horizontal and vertical beam profiles at *z* = 40 cm

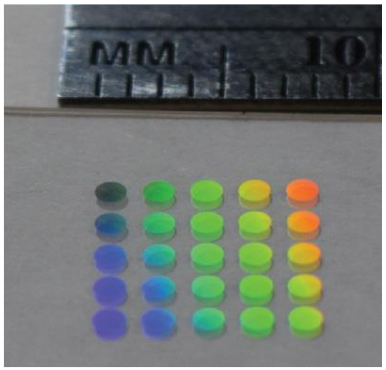


Collimation using flat metasurface lenses

Flat lenses designed for 4.8 µm QC laser collimation

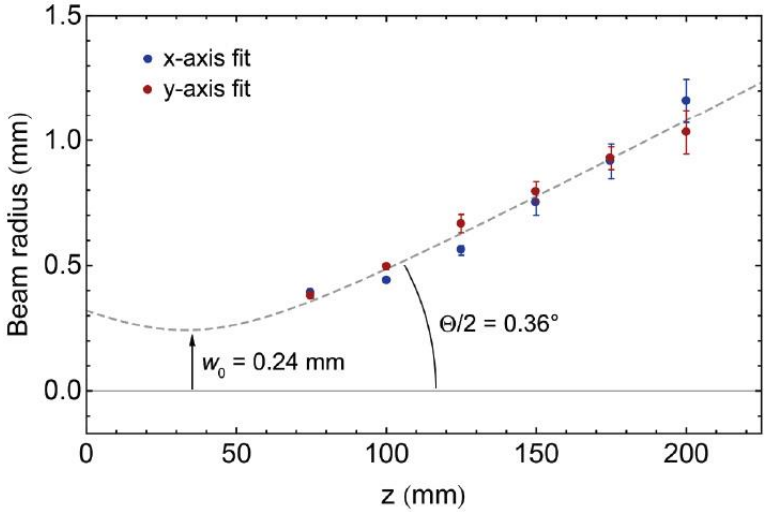


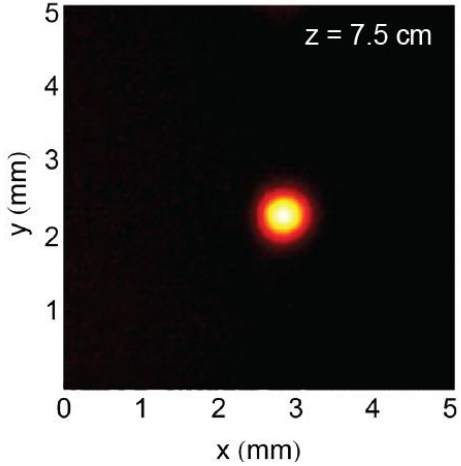




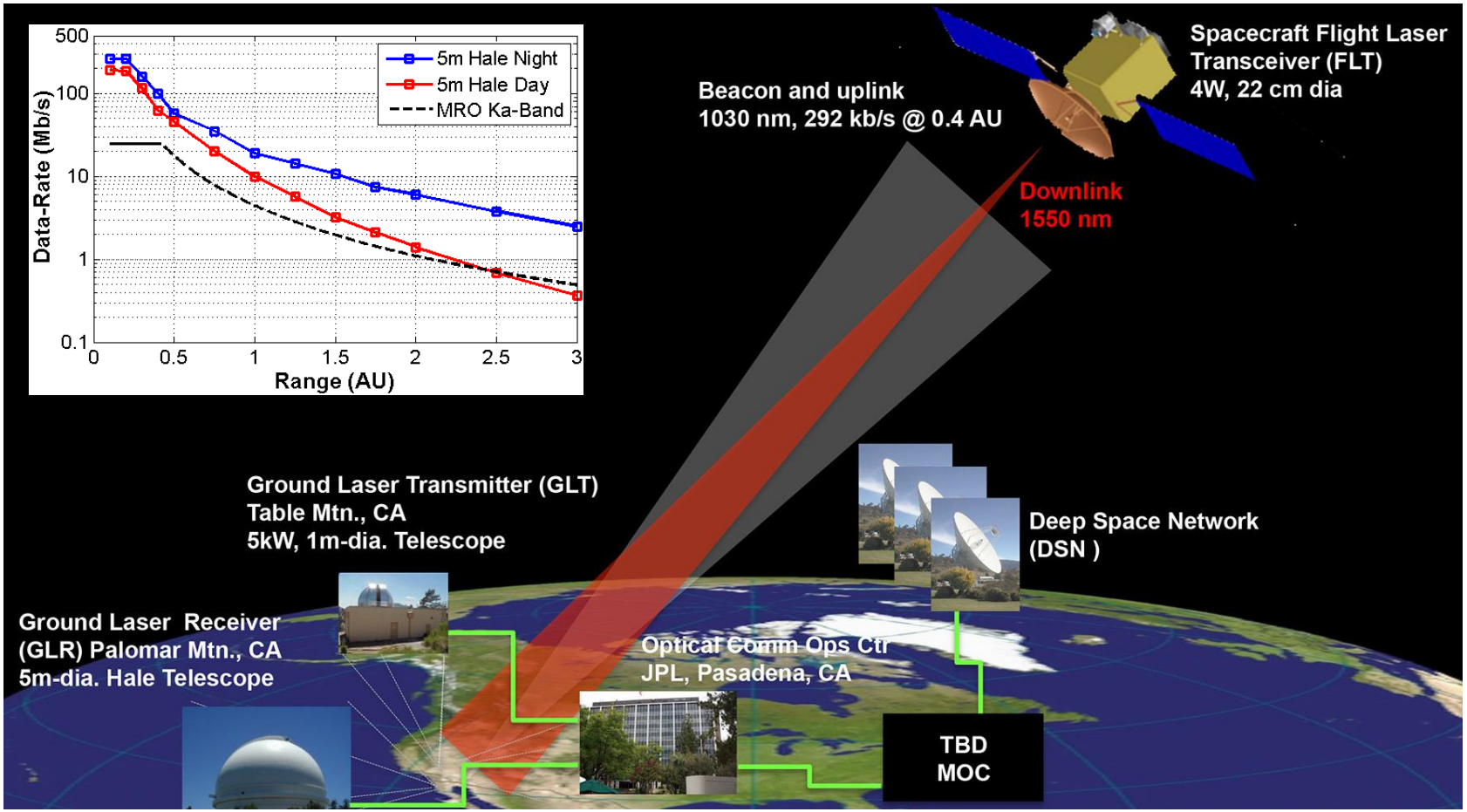
Arabi, *et al.*, *Opt. Express* **23**, 33310 (2015)

Achieved collimation with $M^2 = 1.02$





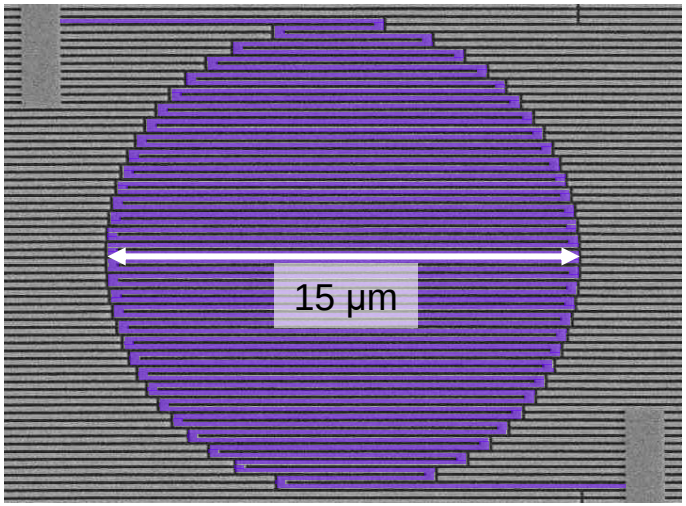
Deep space optical communication with SNSPD ground receivers



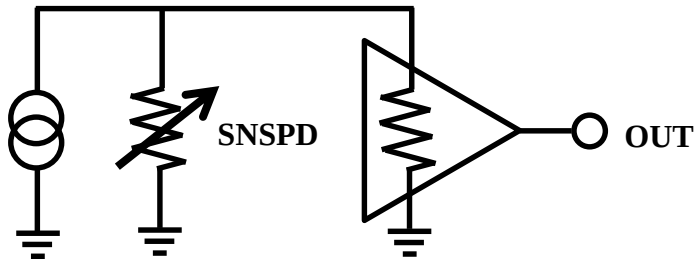
Ground receiver requires an efficient, photon-counting detector at 1550 nm

SNSPD principle of operation

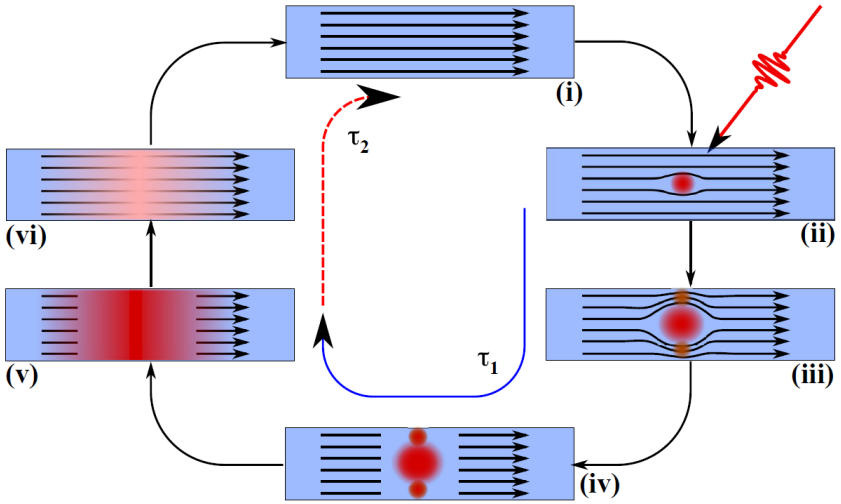
WSi-based single-nanowire detector

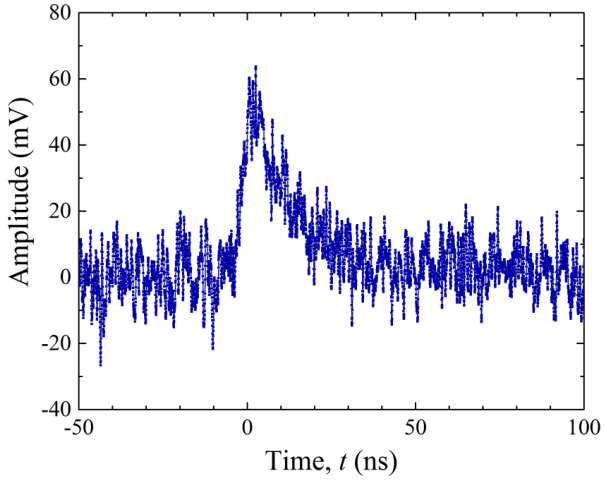


Readout concept



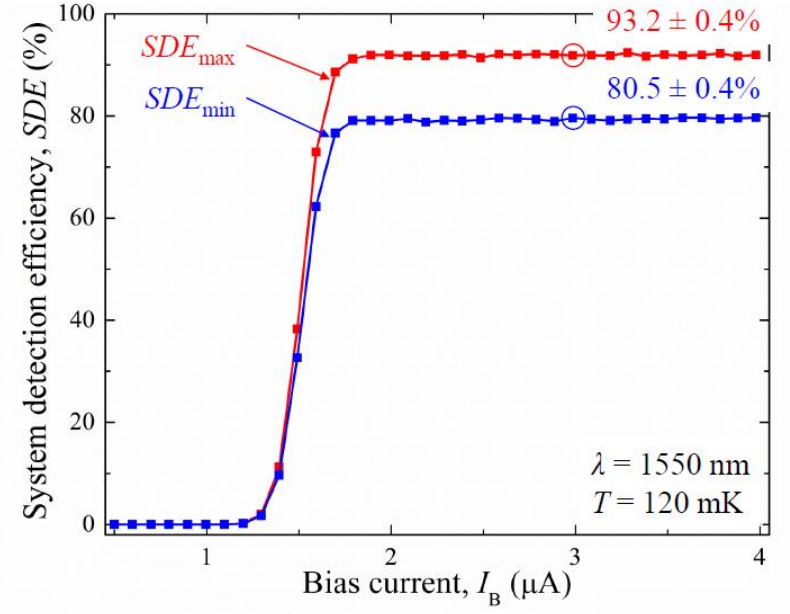
SNSPD detection process



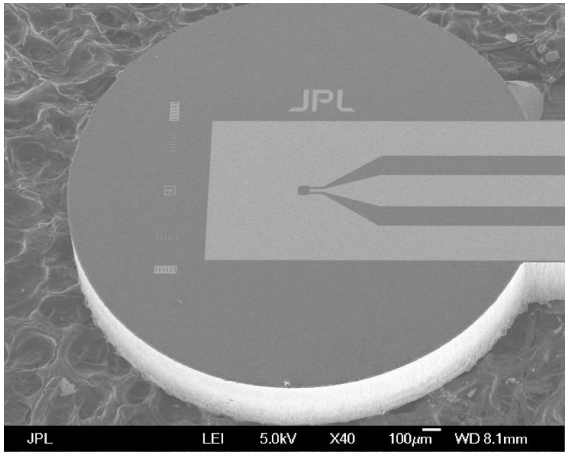


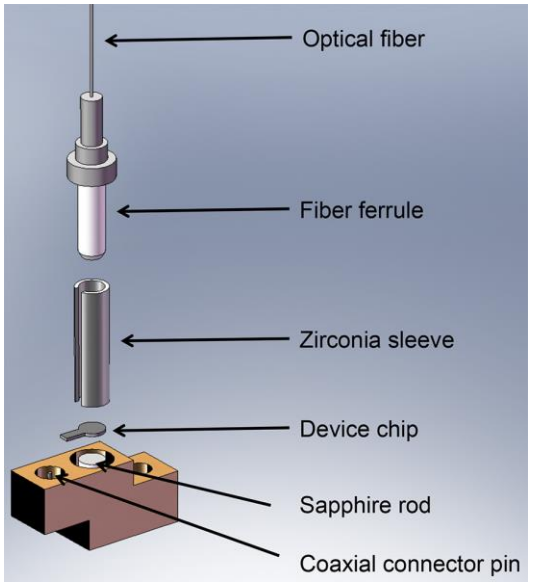
High-efficiency single-pixel SNSPDs

WSi-based single-pixel, fiber-coupled detectors
(in collaboration with S.W. Nam, *et al.*, NIST)



Marsili, *et al.*, *Nature Photon.* **7**, 210 (2013)





Miller, *et al.*, *Opt. Express* **19**, 9102 (2011)

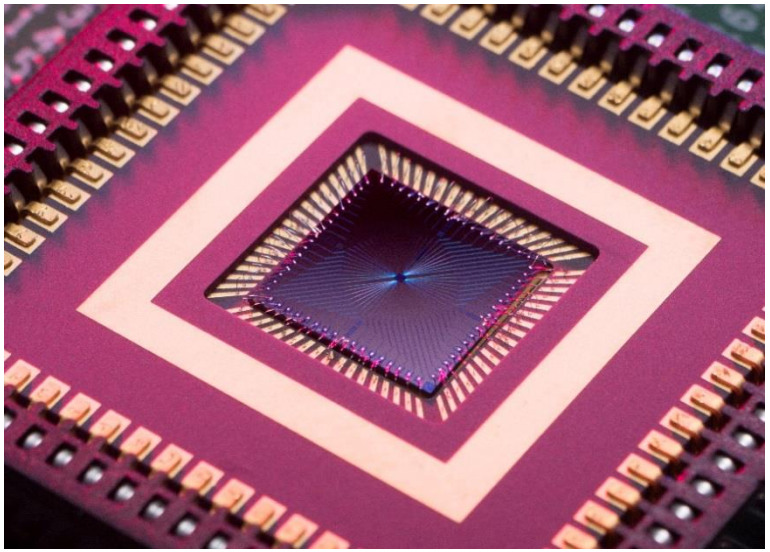
Deep Space Optical Communication (DSOC) project

Kicking off now as a NASA Technology Demonstration Mission

Planned to launch with Discovery spacecraft in 2021

Goal is to transmit 264 Mbps from 0.16 AU, 45 kbps from 2.6 AU

Ground terminal at the 5 m Palomar Hale telescope to use a 64-pixel WSi SNSPD array

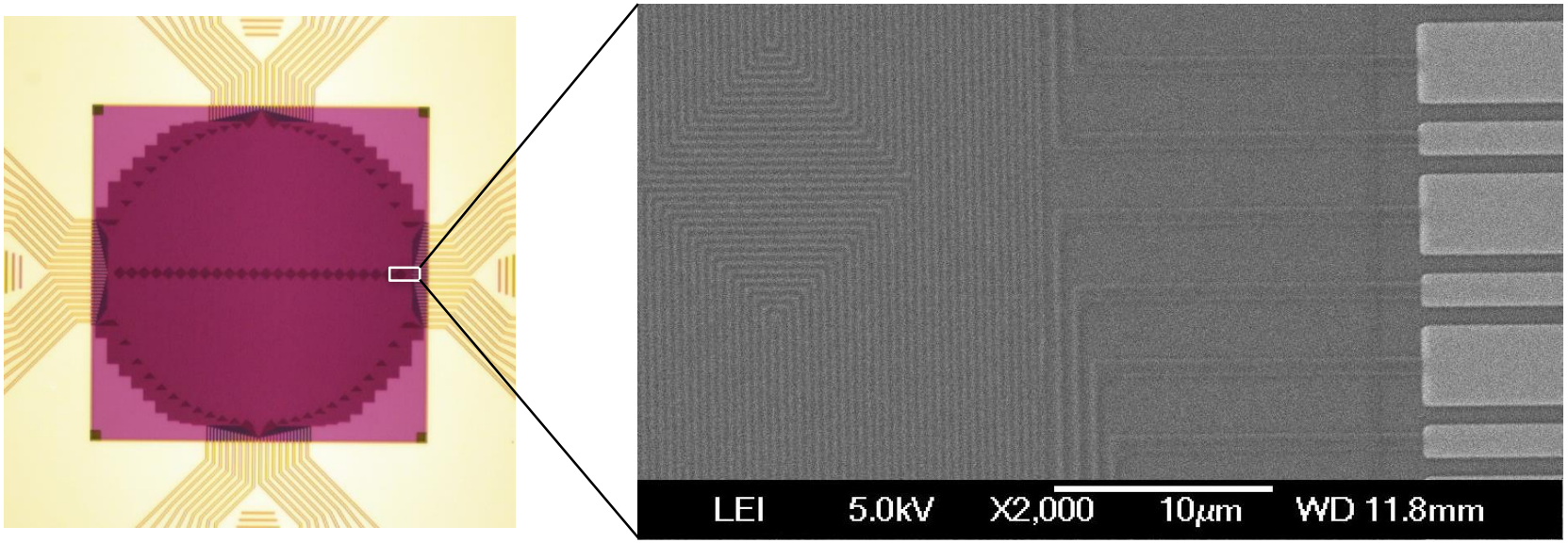


High-count-rate SNSPD arrays

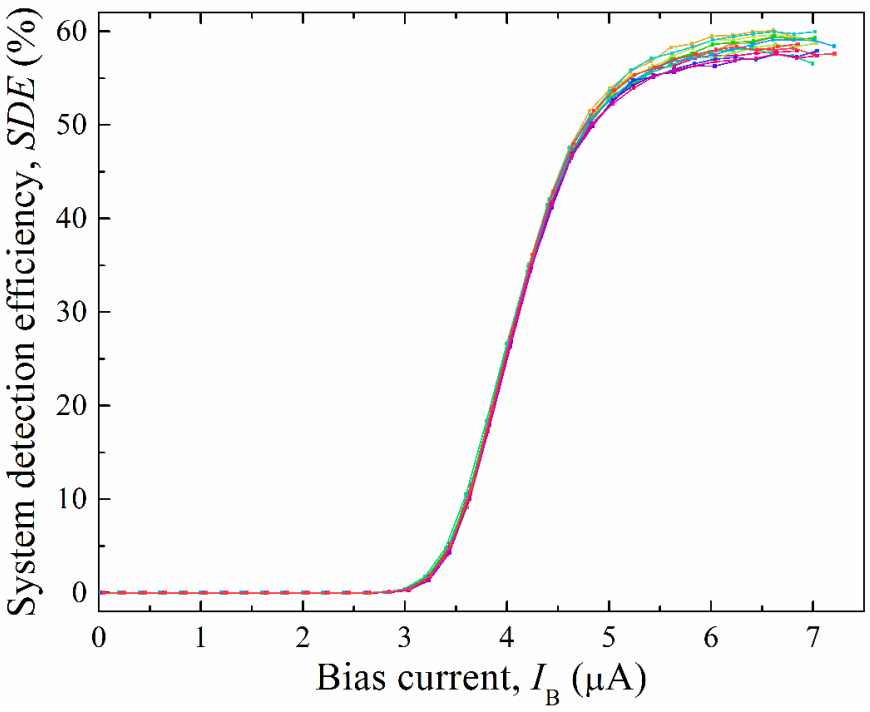
64-pixel SNSPD array with buried reflector and topside coating optimized for 1550 nm

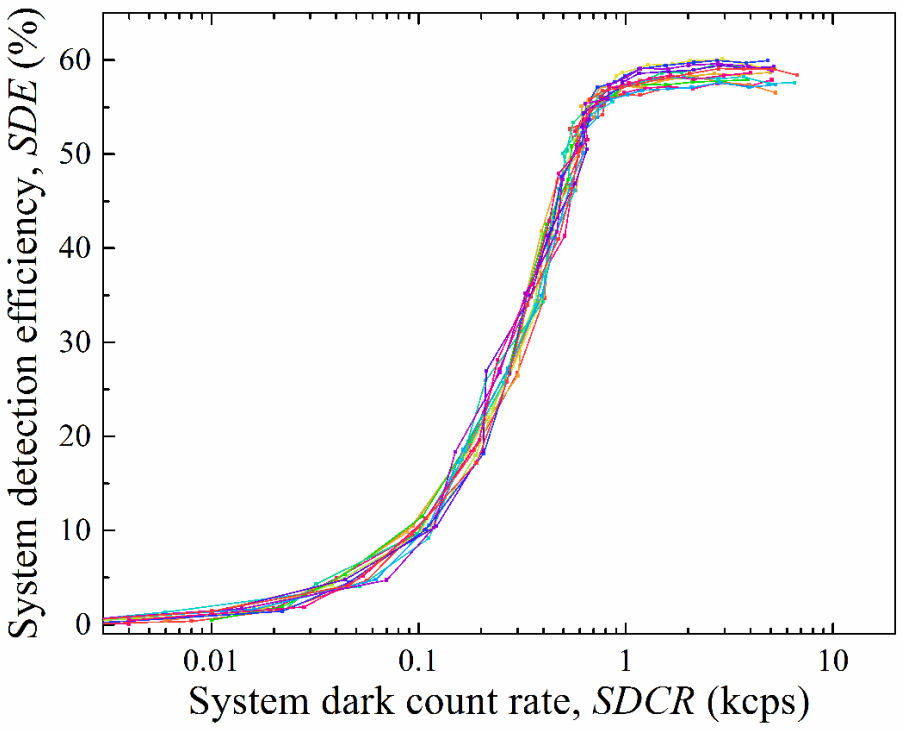
320-µm diameter free-space coupled active area, 4 quadrants, 16 wires per quadrant

10% nanowire fill factor: 4.5 x 160 nm wires on a 1.6 µm pitch



64-pixel SNSPD array performance



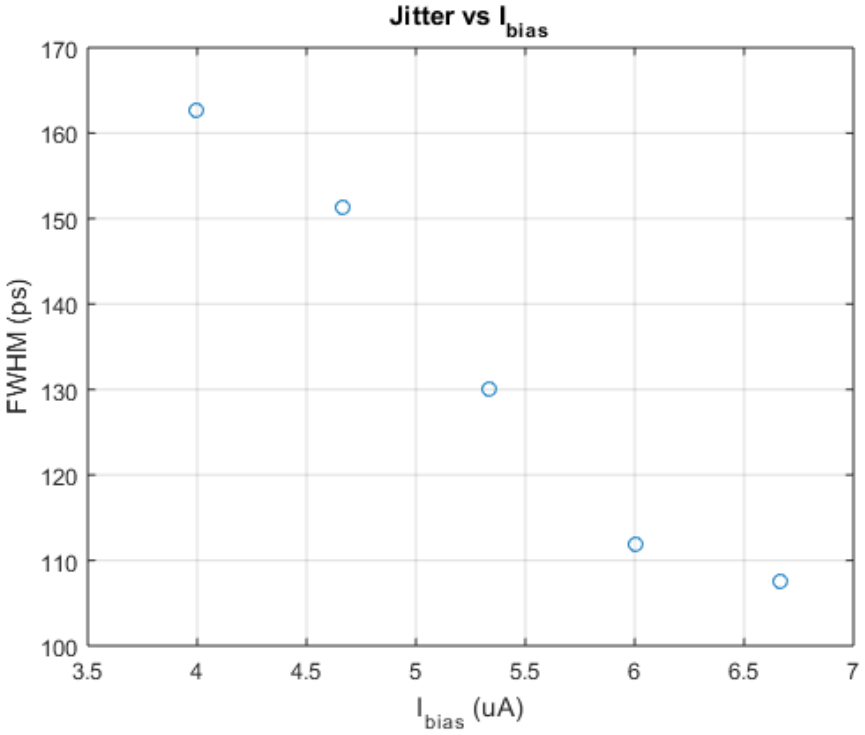


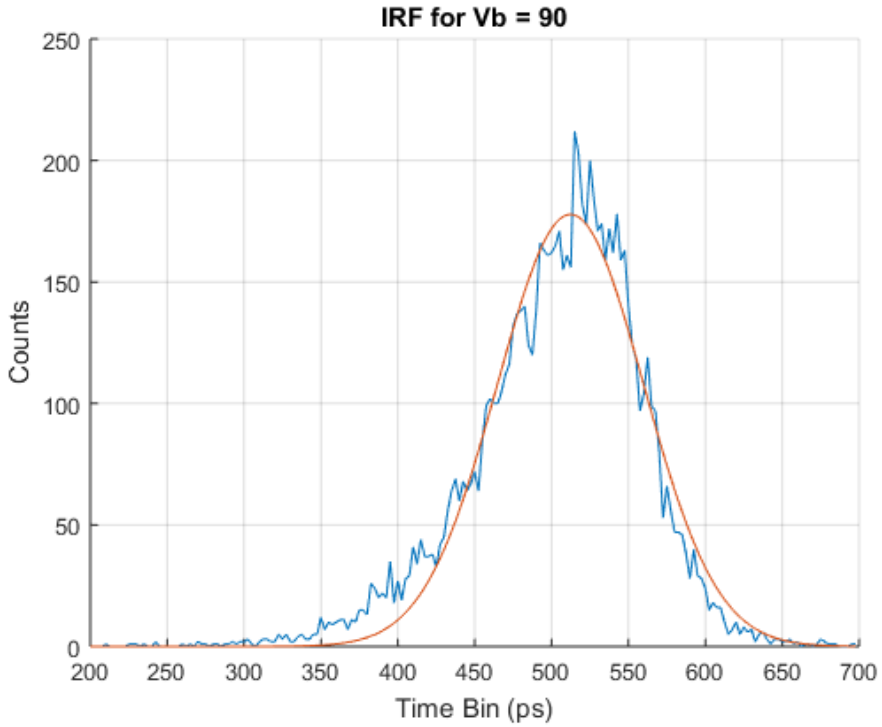
Measured 55% efficiency for 31 of 32 wires

1.3 Gcps (assuming 60 active pixels)

<7 kcps dark count rate per pixel at maximum detection efficiency

64-pixel SNSPD array performance



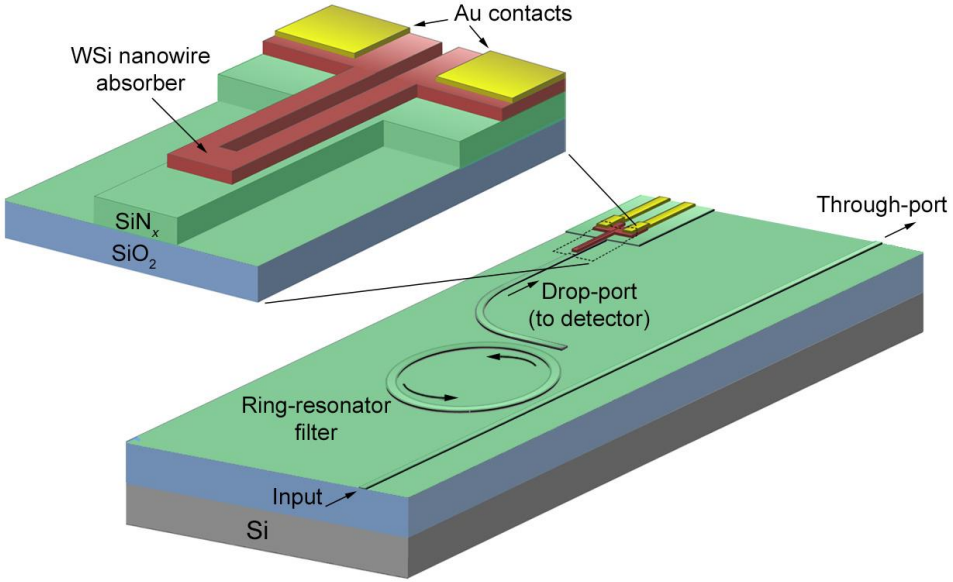


Measured timing jitter of <170 ps FWHM across detector bias plateau

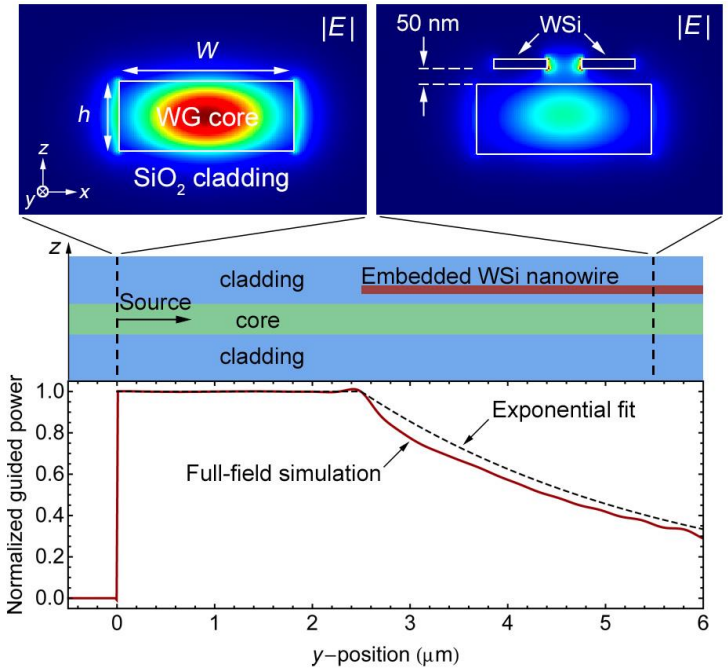
Bias scaling suggests that readout noise is the dominant jitter mechanism

Waveguide-integrated SNSPDs

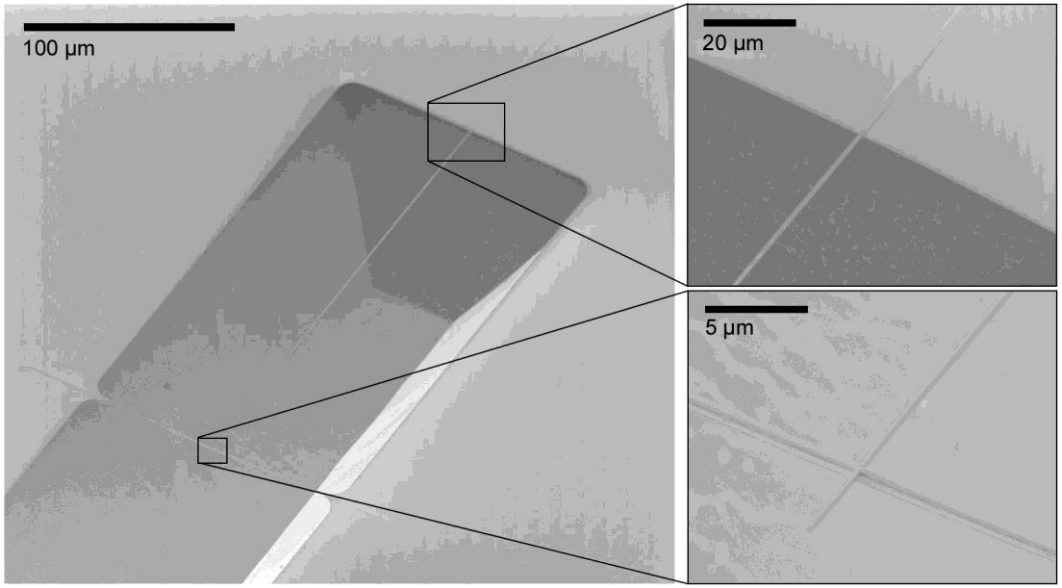
Single 5-nm-thick WSi hairpin patterned on top of a single-mode low-stress SiN_x waveguide

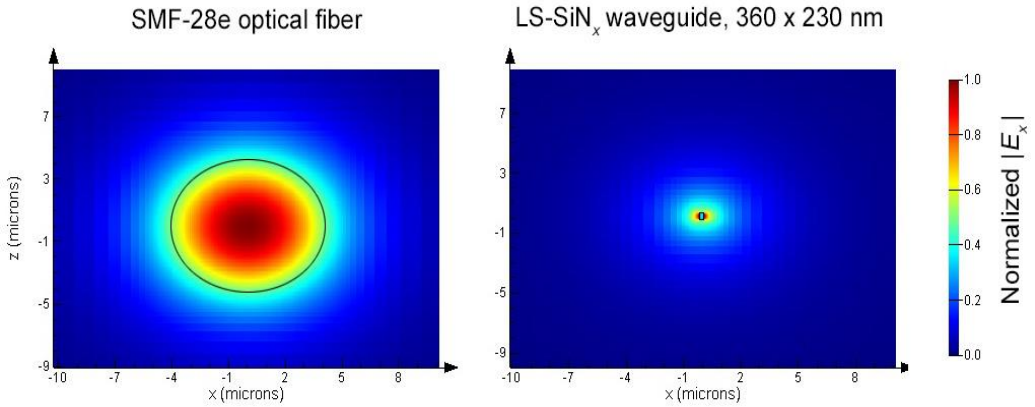


FDTD simulations indicate an expected absorption length of <10 μm for the fundamental TE mode



Cryo-compatible suspended inverse-taper fiber couplers

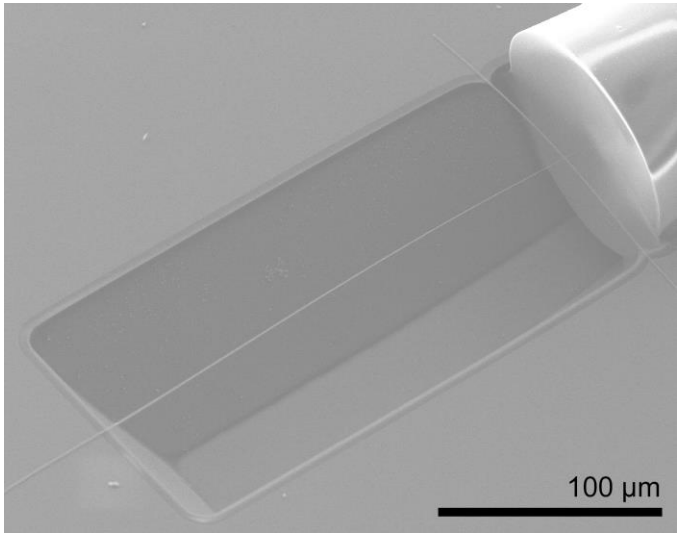




Suspended low-stress SiN_x undercut by wet chemical etching

Mode-matching to standard fiber indicates calculated 86% coupling efficiency

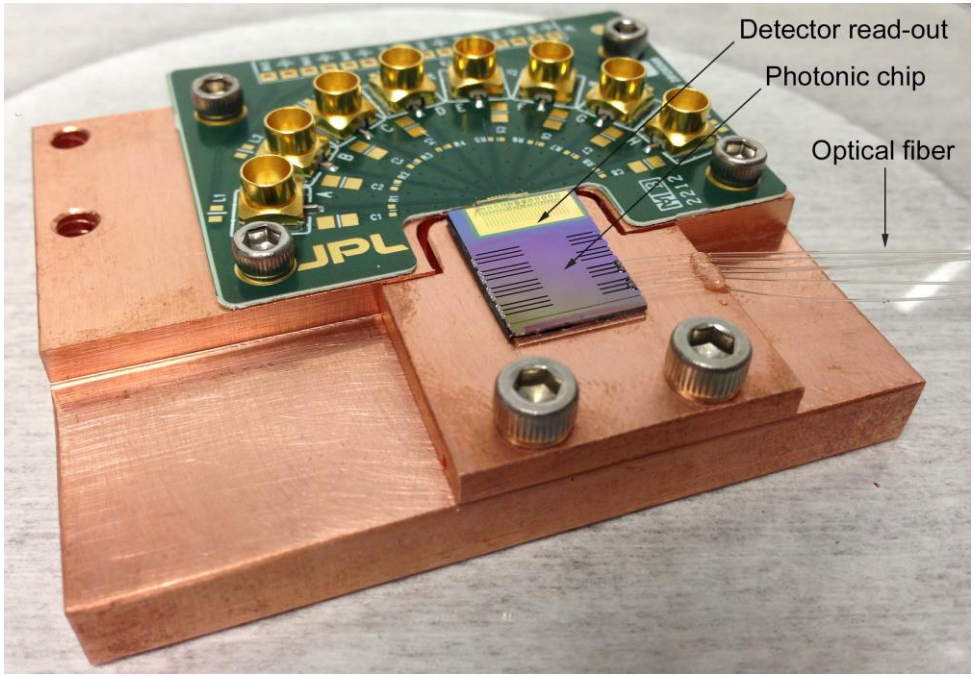
Additional scattering from tether and substrate interface reduces calculated efficiency to 42%

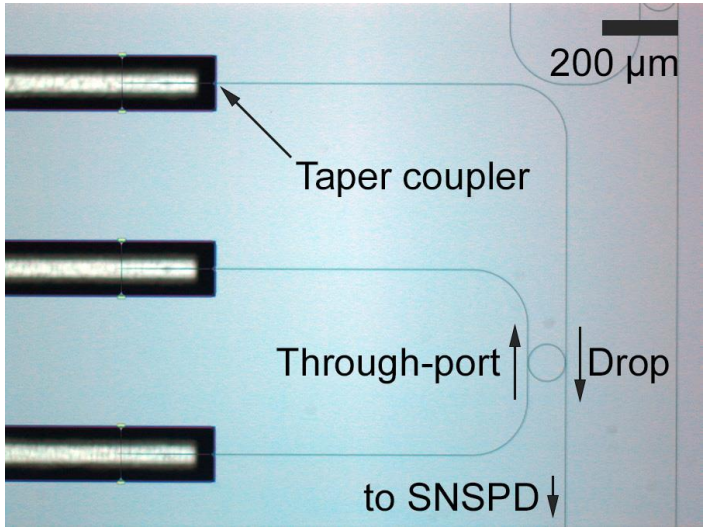


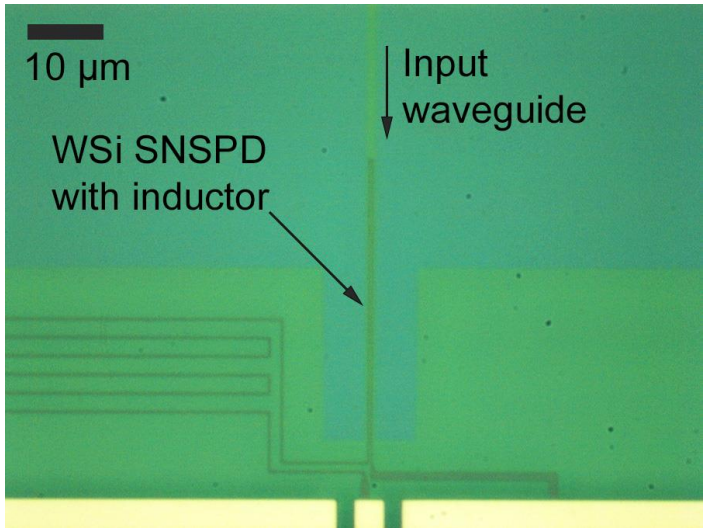
Complete WG-SNSPD photonic chip

Three nominally identical fiber ports per SNSPD and eight SNSPDs per chip

Enables independent characterization of waveguide loss and detector performance





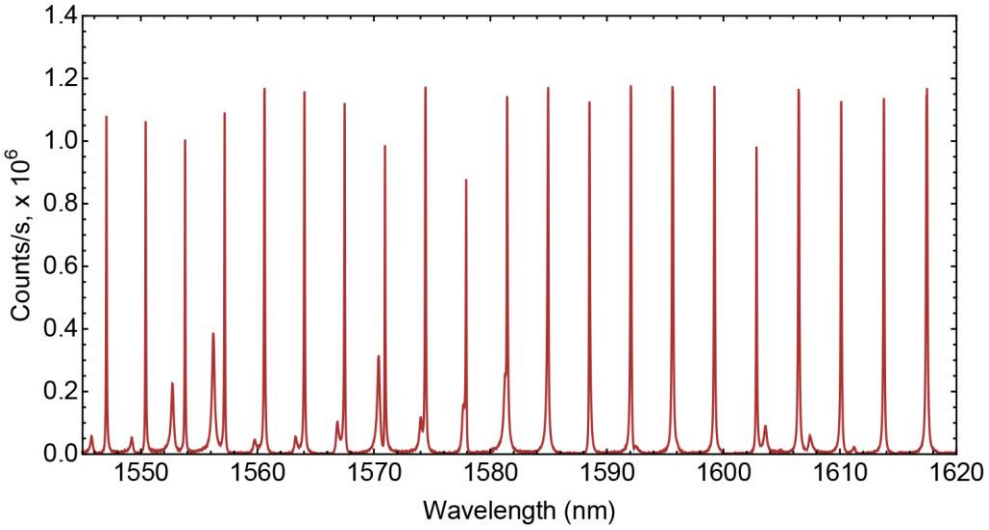


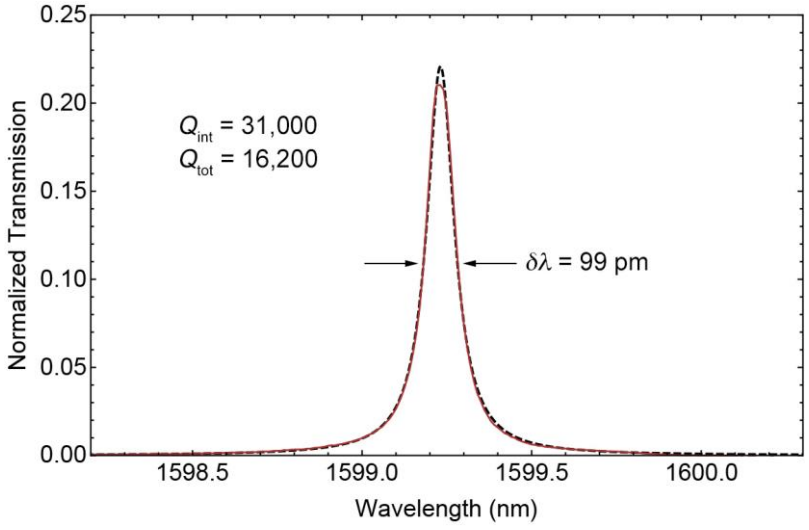
Count rate vs. wavelength

Detector measurements show spectral filtering using a SNSPD coupled to a ring-resonator drop-port

FSR equivalent to conventional detector measurements, confirming TE mode operation

Weaker (more dispersive) resonances likely related to TM mode



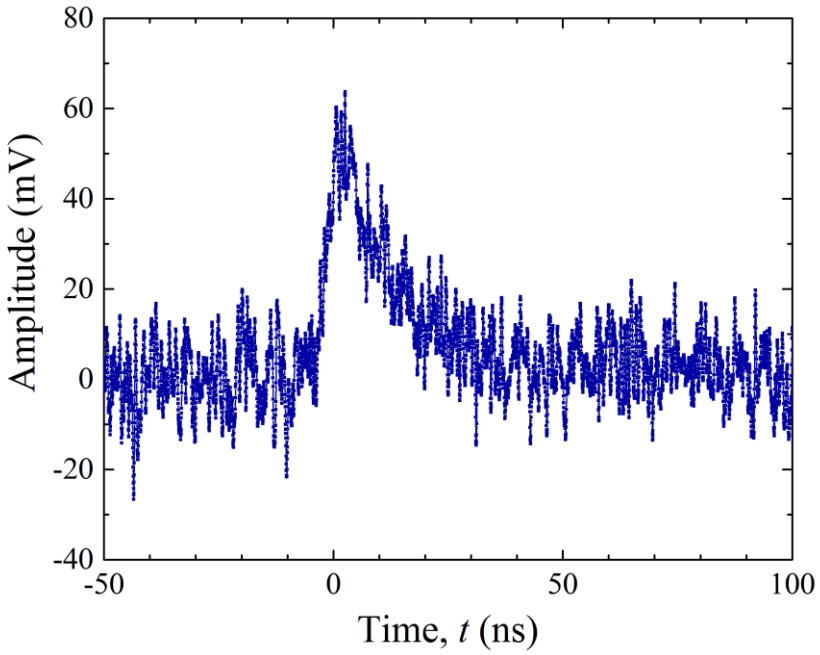


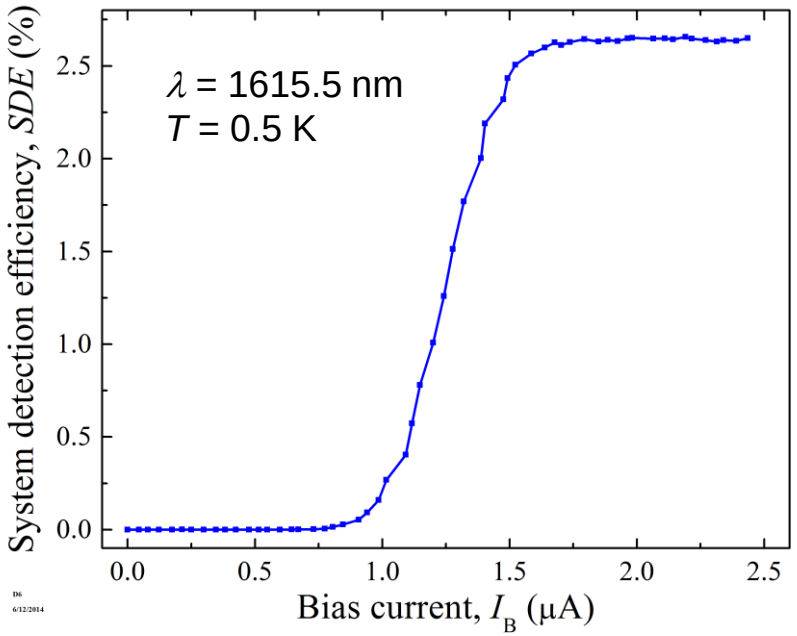
Waveguide-integrated SNSPD performance

Detector pulses show recovery time of ~10 ns

Saturation of counts with bias current indicates high internal efficiency

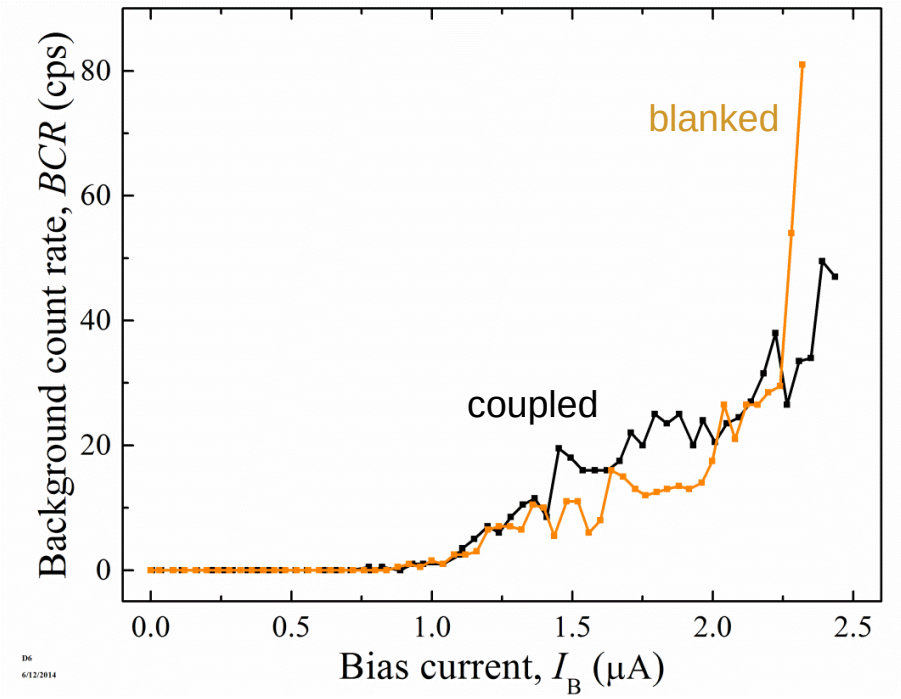
System detection efficiency limited by couplers and waveguide propagation loss





Waveguide-integrated SNSPD dark counts

Low measured dark counts with and without fiber feed-through connected



Acknowledgements

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Matthew Shaw, Andrew Beyer, Francesco Marsili, Jason Allmaras, and Bill Farr, *JPL*

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